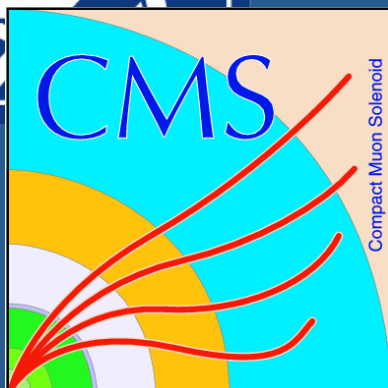


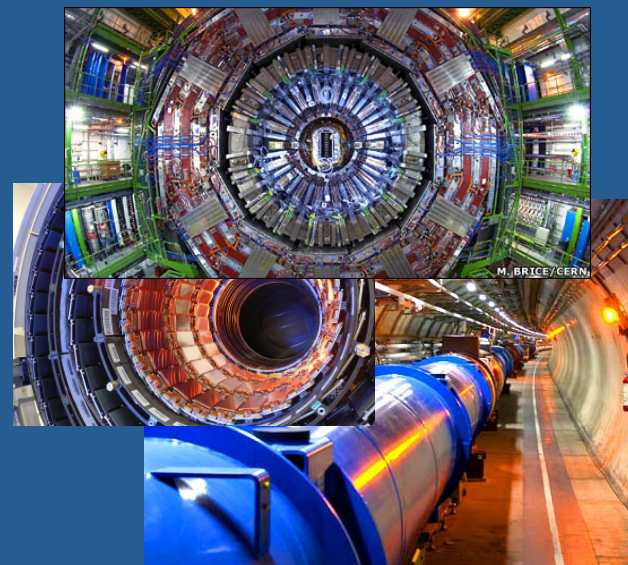
Observation of $t\bar{t}H$ Production

Prof. Chris Neu
Department of Physics
University of Virginia



*On behalf of
the CMS Collaboration*

Fermilab
4 May 2018



Discovery of the Higgs Boson

- This discovery has been billed as one of the most important scientific discoveries of the last half-century
- A great advance in our understanding of the dynamics of the fundamental world
- Now nearly 6 years on, our work continues.
- **Much remains to be known about this particle**



Outline:

- Characterizing the observed Higgs boson
- Missing Piece: The top-Higgs coupling
- Status of the top-Higgs coupling pursuit at CMS
- Precision top-Higgs physics
- Summary and looking forward

Higgs Characterization: Couplings

- In the post-discovery era focus:
 - Is this the Higgs Boson of the Standard Model?*
- The coupling of this Higgs boson to the other fundamental particles is one distinguishing feature:
 - Unambiguously predicted in the SM
 - BSM physics (massive new particles or new dynamics) predicted to impact the observed coupling strengths

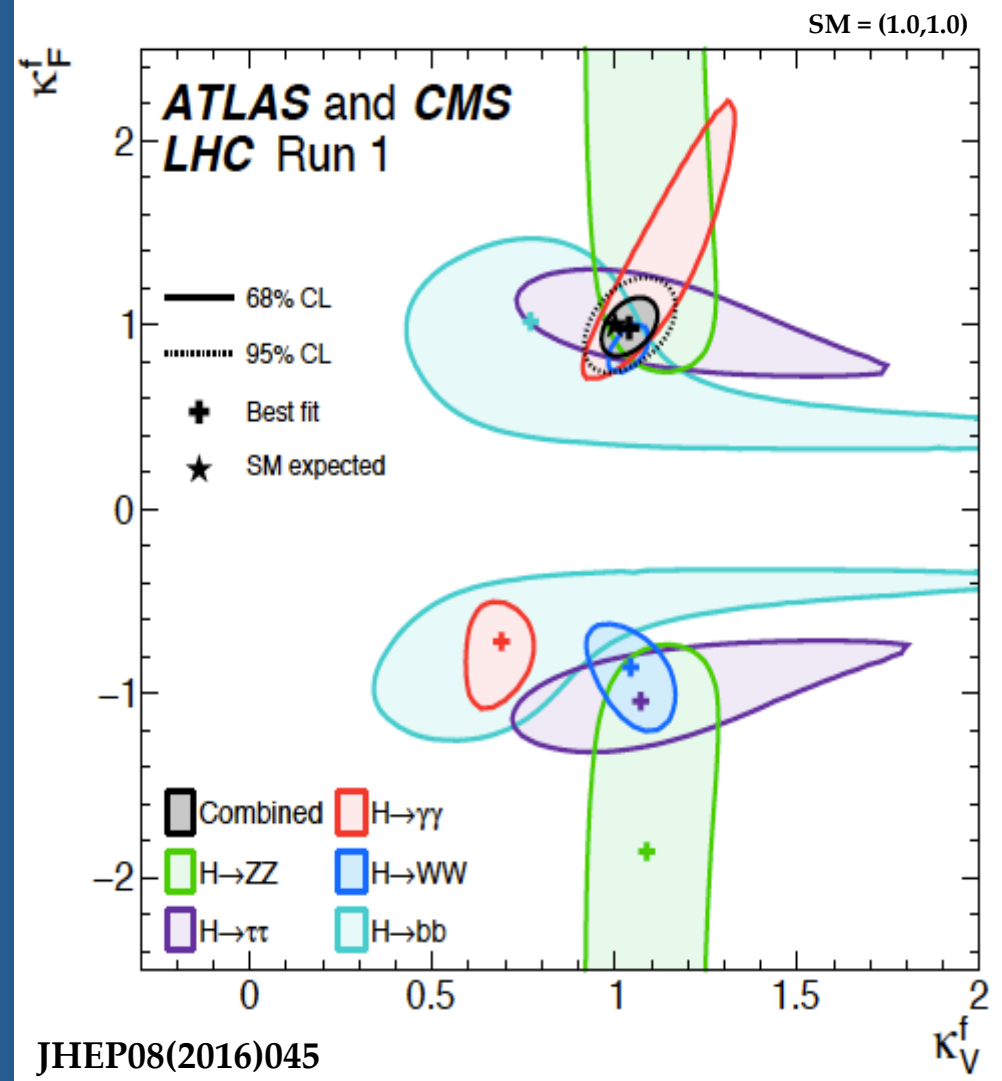
SM:

$$g_{HVV} = 2 \frac{m_V^2}{v} \quad g_{Hff} = \frac{m_f}{v}$$



BSM allowance:

$$g_{HVV} = \kappa_V \left(2 \frac{m_V^2}{v} \right) \quad g_{Hff} = \kappa_f \left(\frac{m_f}{v} \right)$$

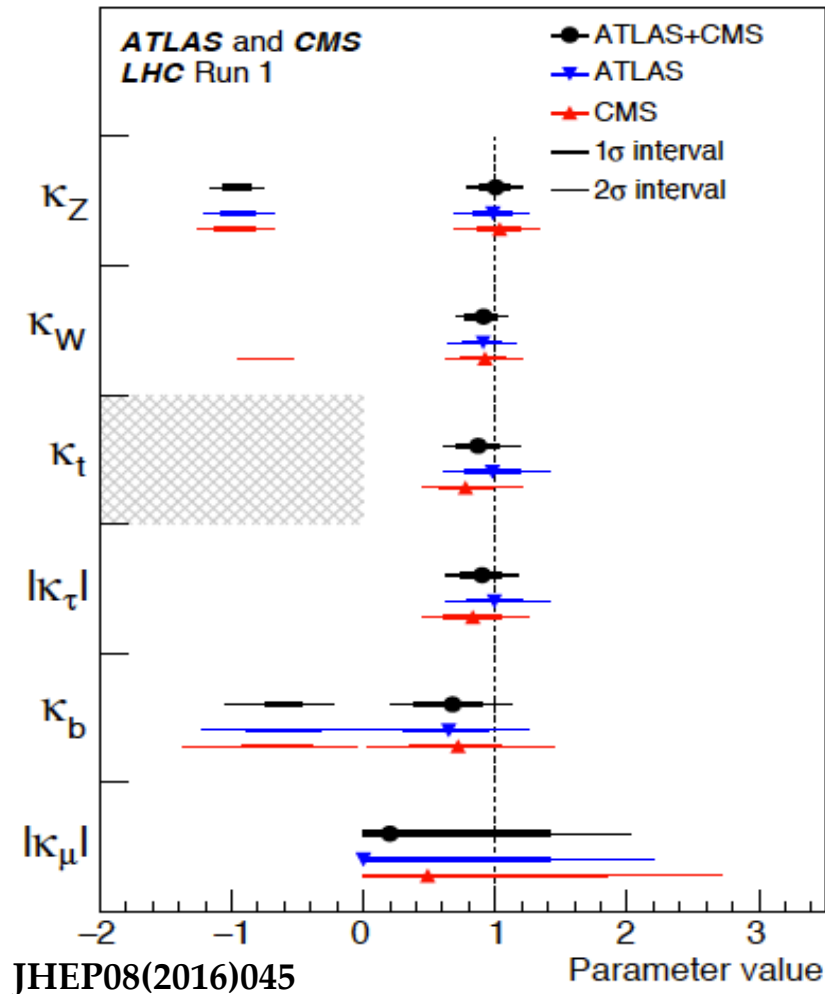


**Fermionic and bosonic coupling modifiers
look very SM-like**

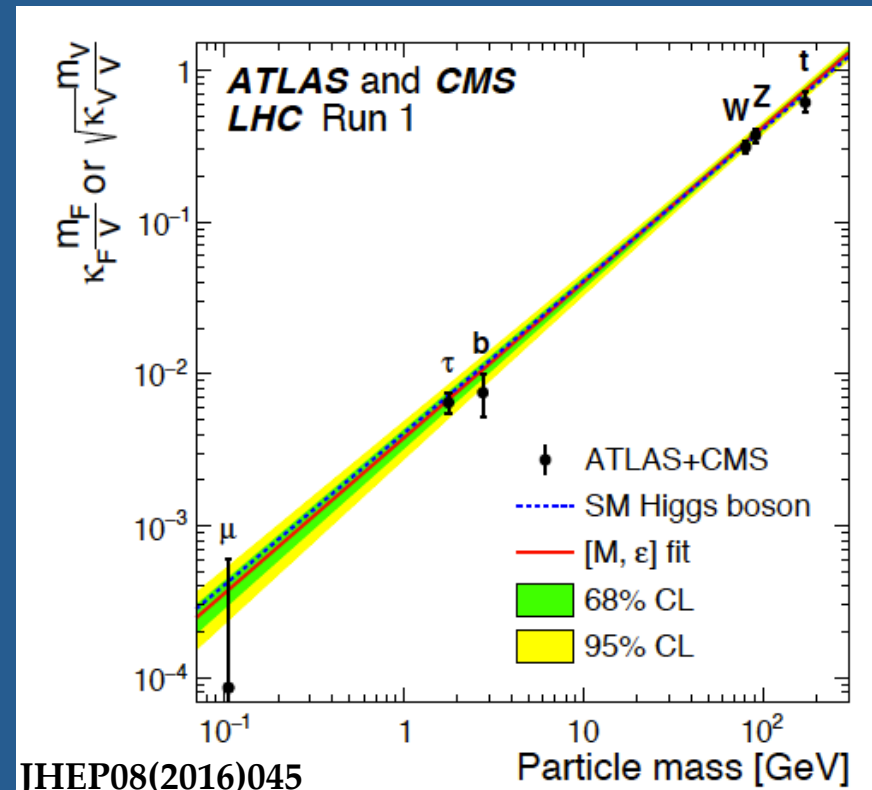


Studies of Higgs Couplings

- Assume SM only particles participating in loop-mediated processes and $\text{BR}(\text{BSM})=0$
- Examine prominent unique couplings that are accessible
- Top-Higgs coupling Y_t is unique:
 - top quark has indirect influence on Higgs production and decay

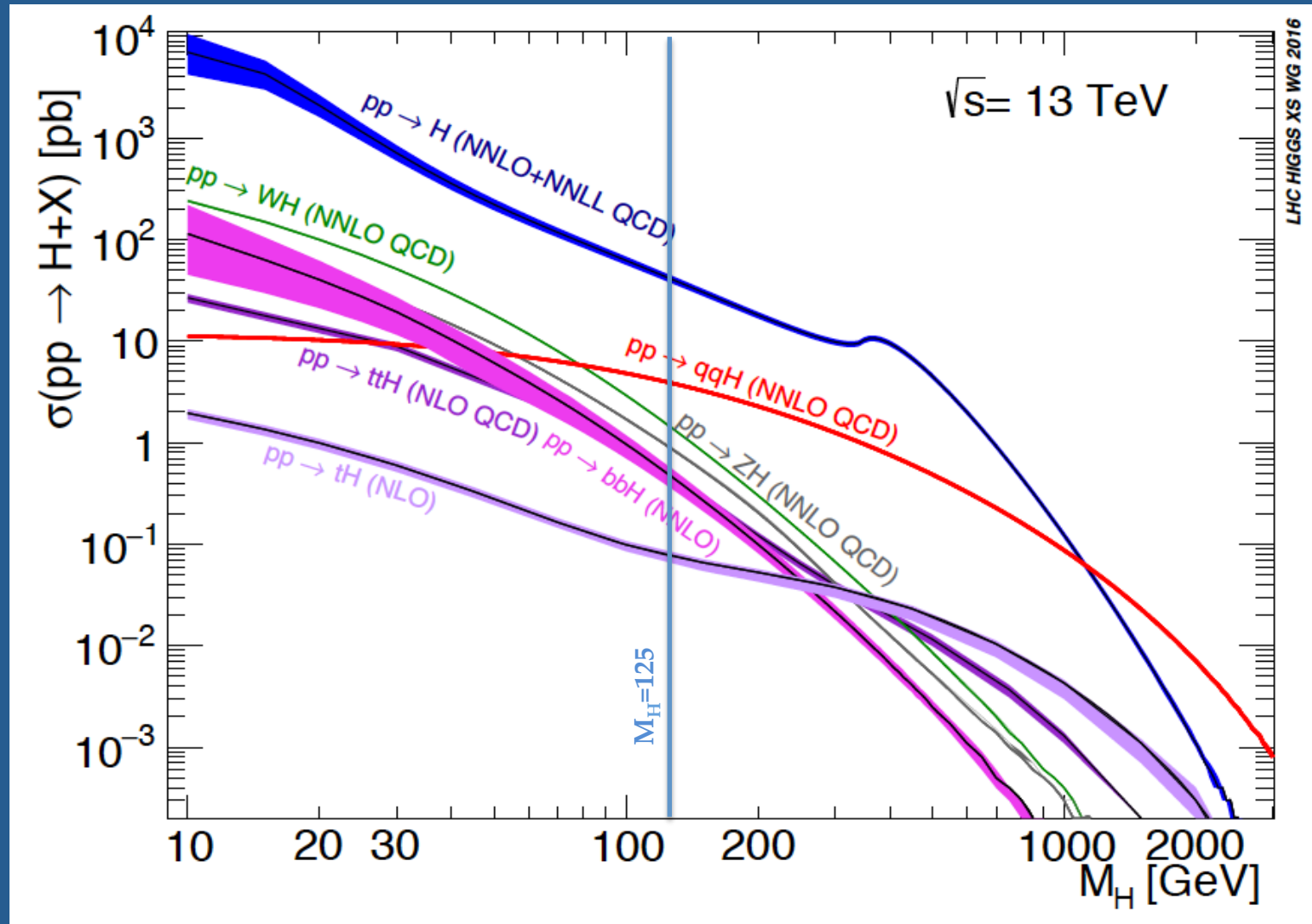


Particle-specific coupling modifiers look very SM-like assuming no influential BSM content



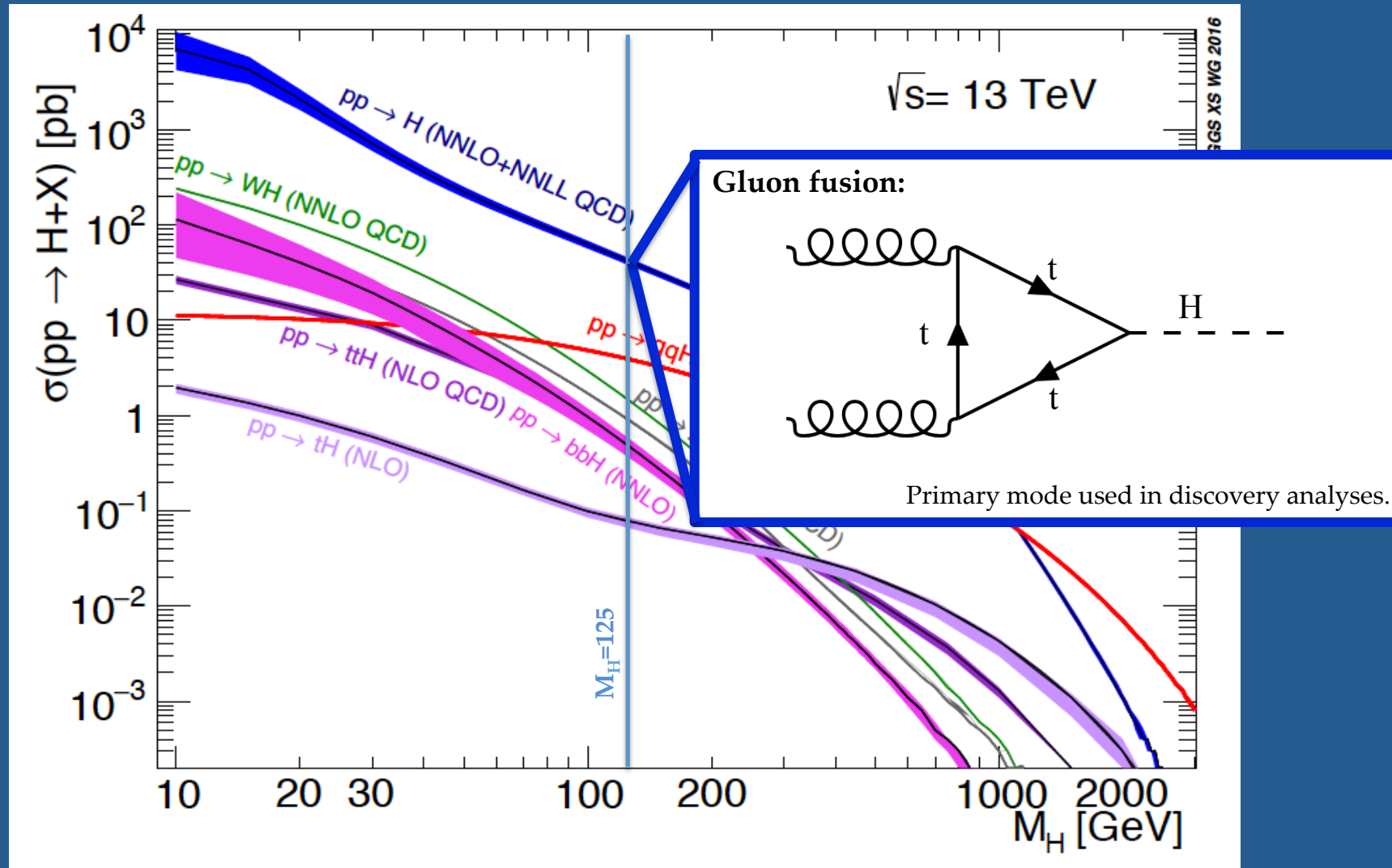
Higgs Production: Influence from Top

Workhorse analyses probe the top-Higgs coupling on the production side:

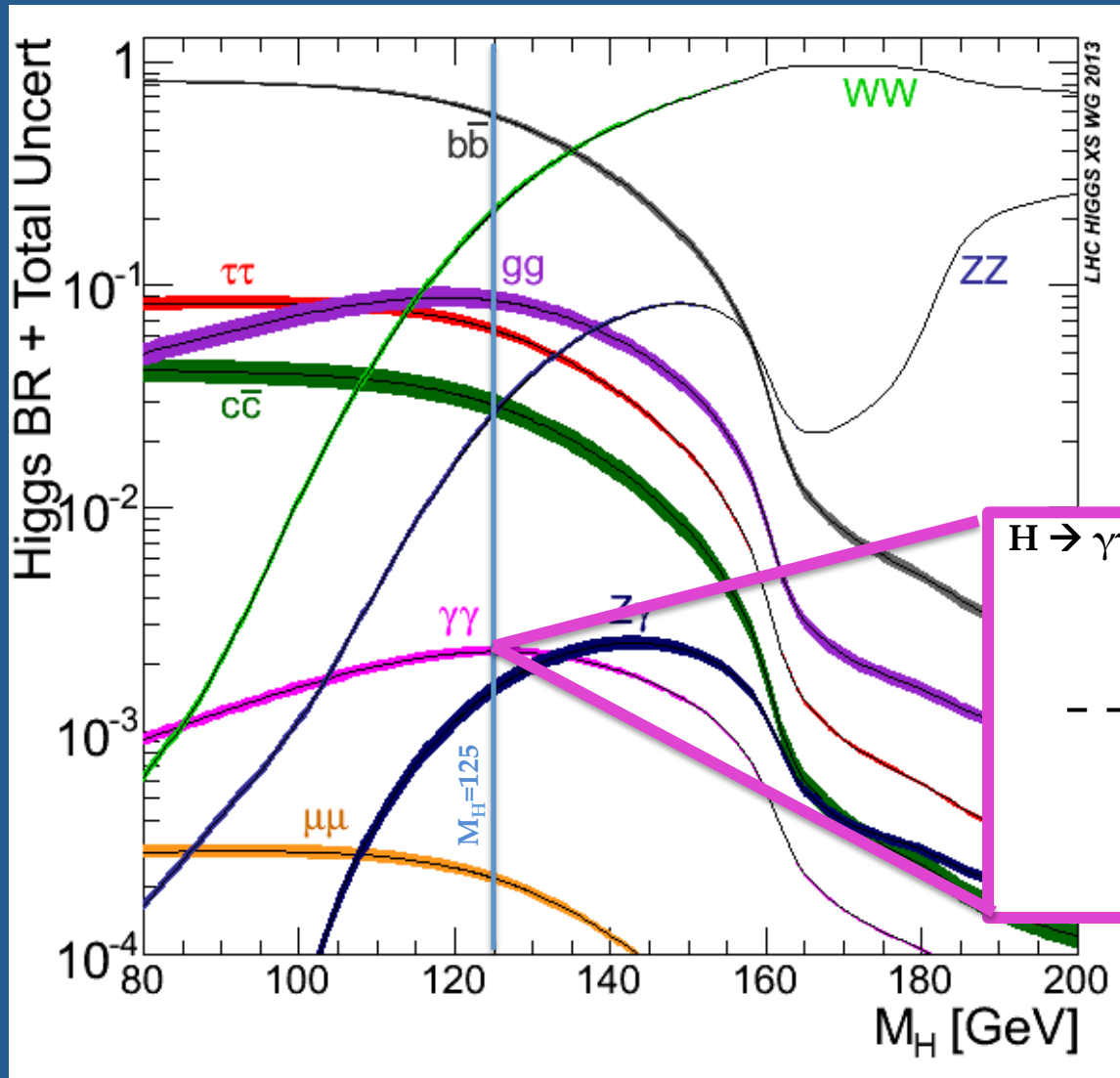


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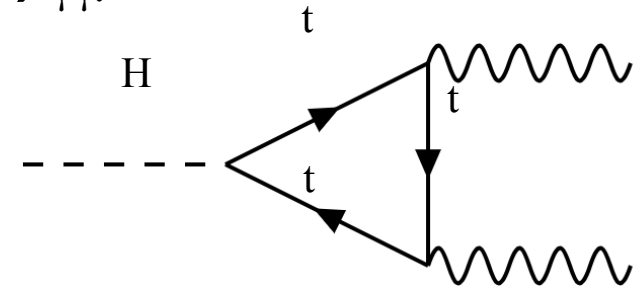


Higgs Decay: Influence from Top



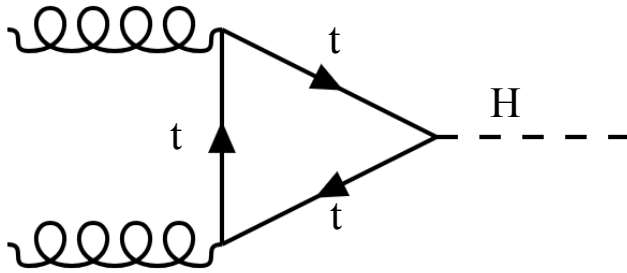
Similar top-quark mediated loops on the decay side, in the case of $H \rightarrow \gamma\gamma$.

$H \rightarrow \gamma\gamma$:

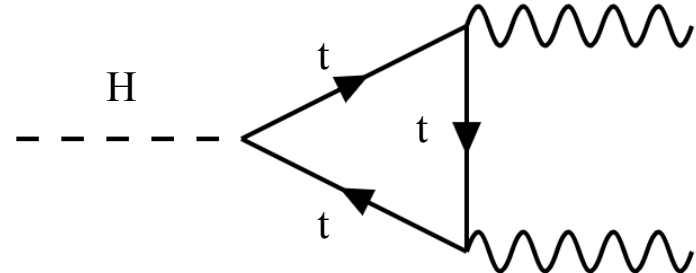


Circumstantial Evidence of Top-Higgs Coupling

Gluon fusion:



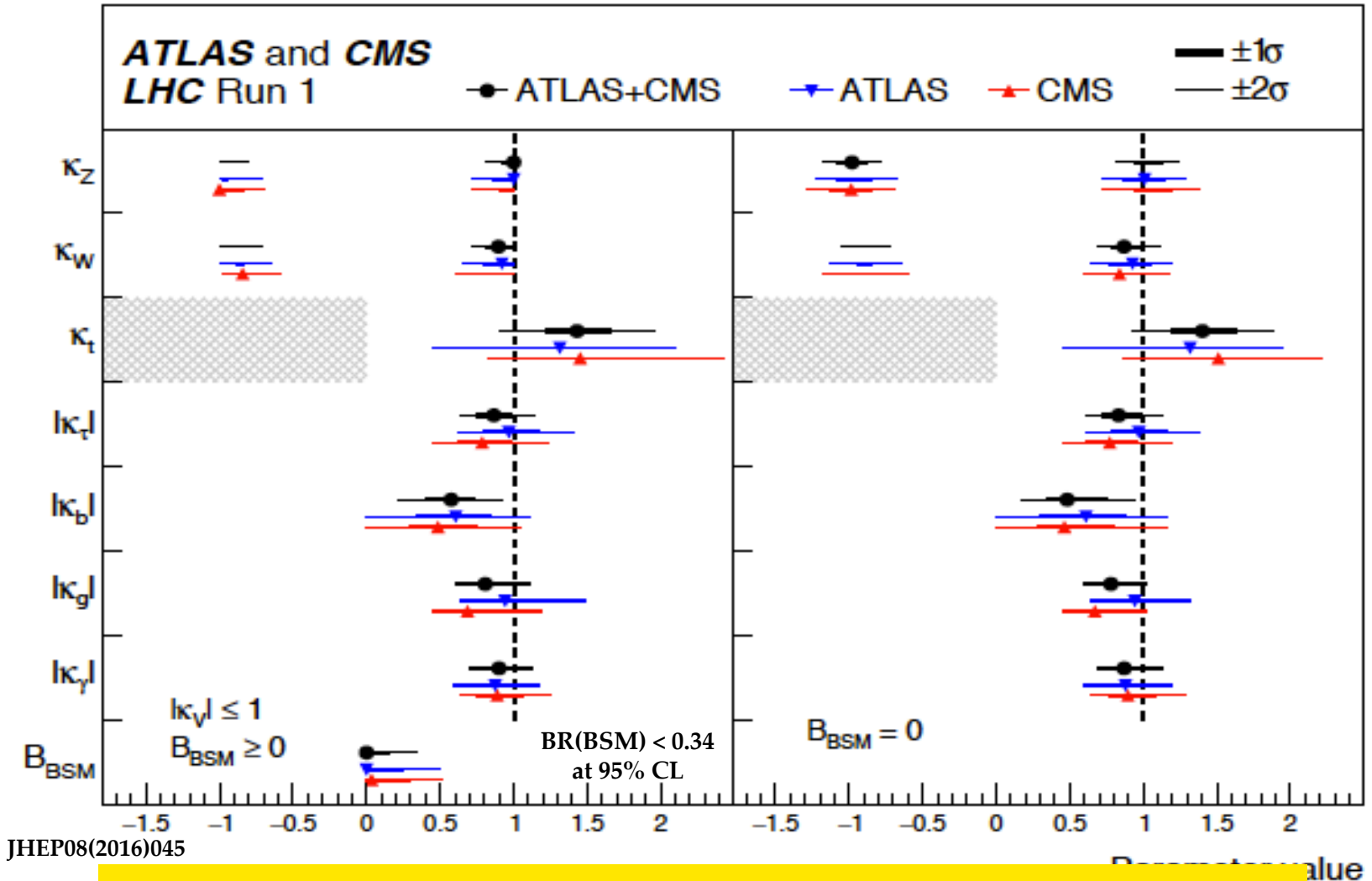
$H \rightarrow \gamma\gamma$:



- Within the SM, these loops are dominated by top quarks:
 - In gluon fusion, need something massive that participates in the strong interaction \rightarrow top quark drives this loop, followed by b's...
 - In $H \rightarrow \gamma\gamma$, need something massive that participates in the EM interaction \rightarrow top quark drives this loop, followed by W's...
- Results presented so far assume there are no exotic contributions to the loops in these processes.
- *But what about the possibility of another suitable particle or particles from outside the norms of the SM?*

Studies of Higgs Couplings

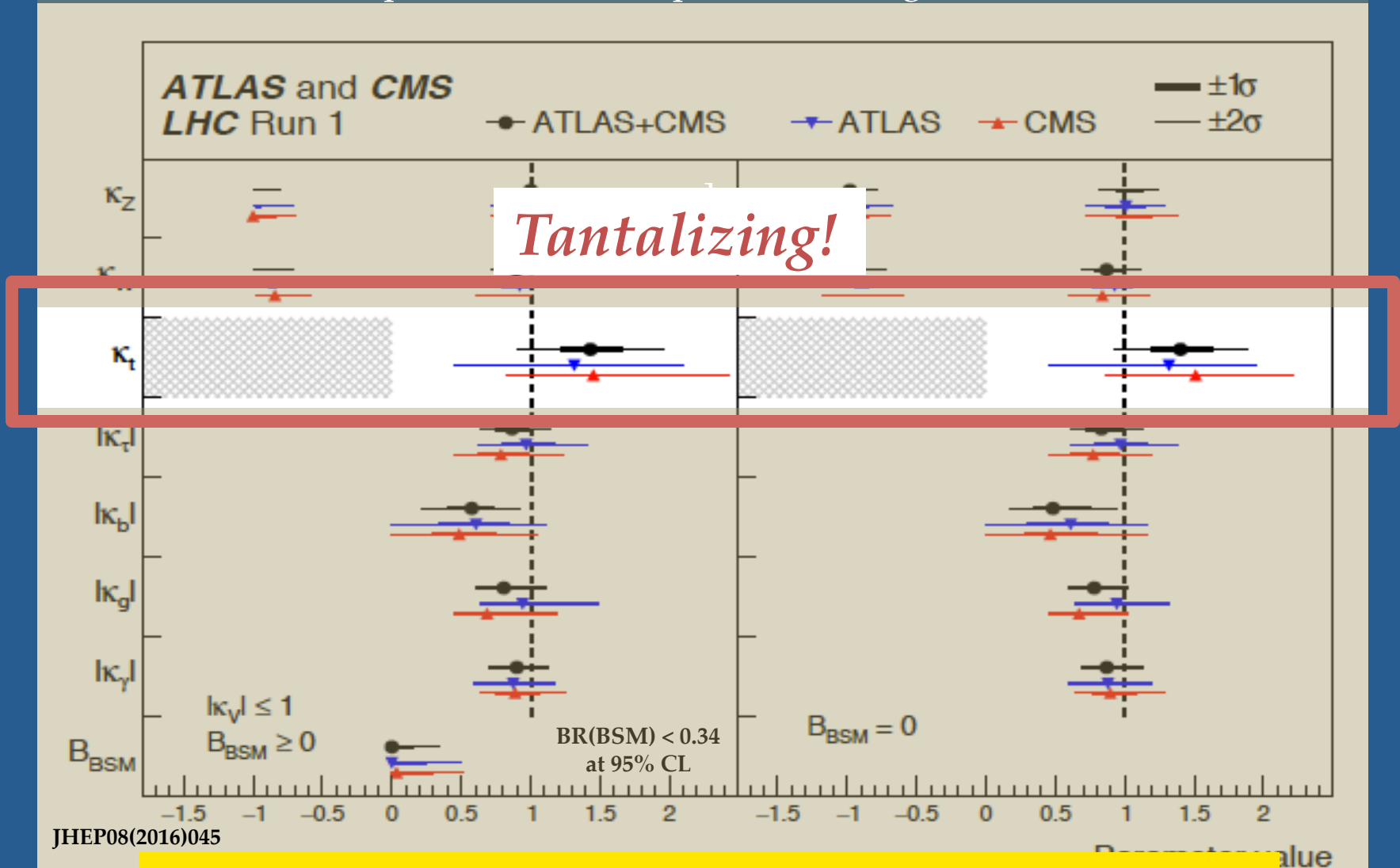
If one allows for the presence of BSM particles, things look somewhat unsettled.



Allowance for BSM contributions – either on the production or decay side, or both – leaves a good deal of phase space still open.

Studies of Higgs Couplings

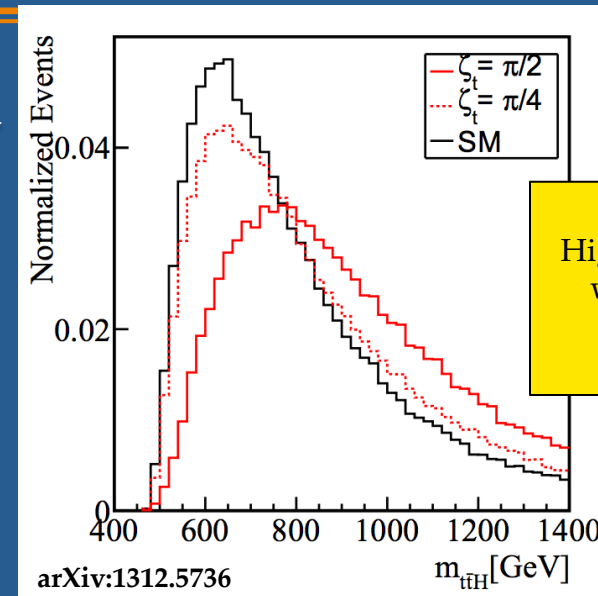
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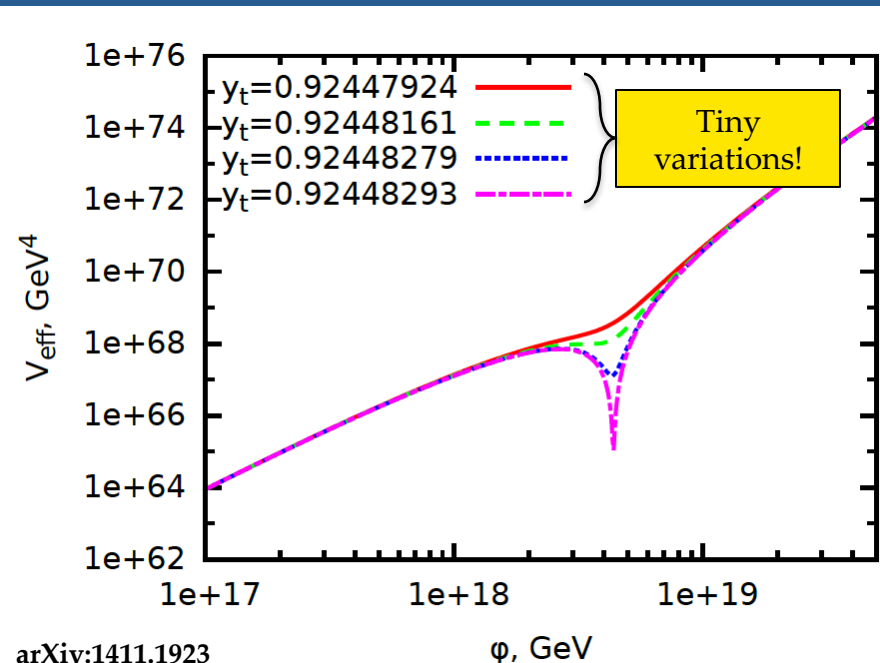
Allowance for BSM contributions – either on the production or decay side, or both – leaves a good deal of phase space still open.

Deeper Significance of Top-Higgs Coupling

- Abundance of BSM theories manifest themselves in an alteration of the top-Higgs dynamics →
- Relatively large m_{top} implies $Y_t \sim 1$:
 - Does this indicate some special role for top in EWSB?
- Y_t is predicted to be by far the largest of all the fermionic couplings
 - Could be essential in identifying unique behavior in fermion sector
- Y_t will be the easiest (only?) up-type fermion coupling we are able to probe
 - Could be window to unforeseen dynamics →
- Extrapolating to Planck energies, Y_t important in effective potential of the Higgs field
 - Largest coupling → small changes to Y_t have large impact
 - Slight deviation in Y_t away from SM → vacuum lifetime is less than the age of the Universe

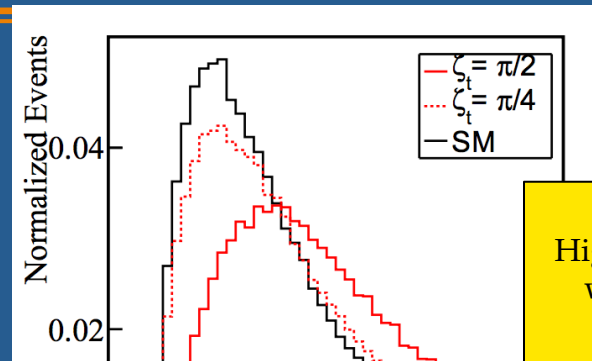


One example:
Higgs-top coupling
with scalar and
pseudoscalar
components.



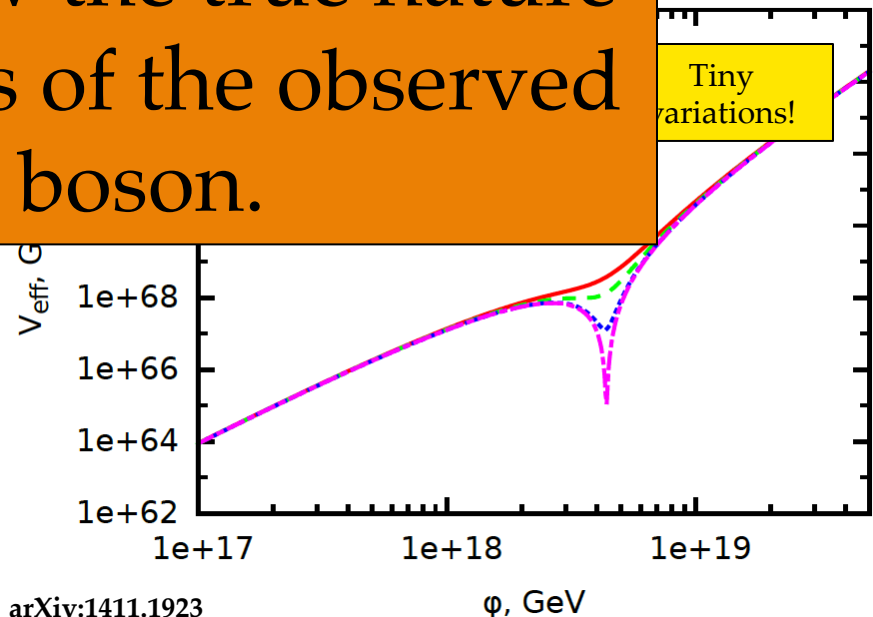
Deeper Significance of Top-Higgs Coupling

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 - Does this indicate some special role for top in EWSB?
- Y_t is predicted fermionic coupling
 - Could be essential for behavior in
- Y_t will be the effective coupling we are interested in
 - Could be with
- Extrapolating to Planck energies, Y_t important in effective potential of the Higgs field
 - Largest coupling \rightarrow small changes to Y_t have large impact
 - Slight deviation in Y_t away from SM \rightarrow vacuum lifetime is less than the age of the Universe

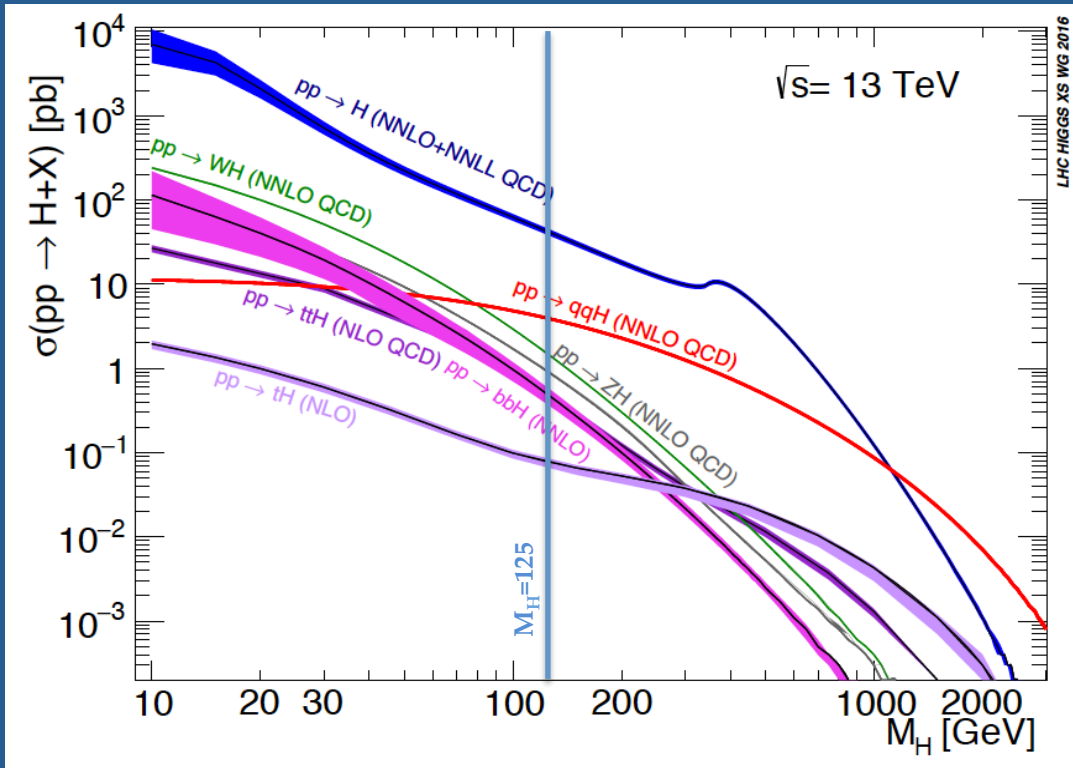


One example:
Higgs-top coupling
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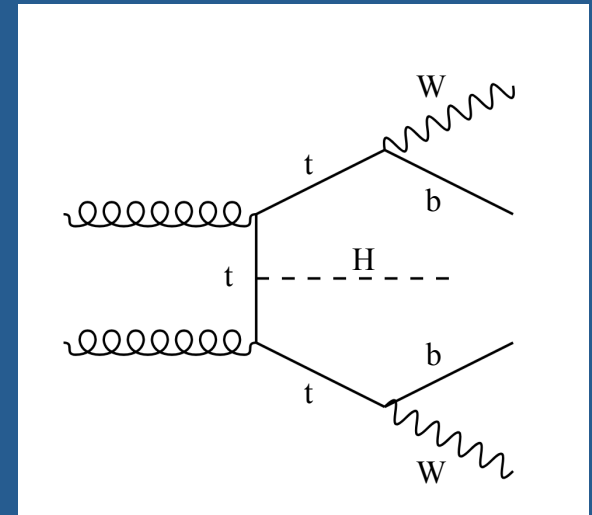
Imperative:
Absolutely need to measure Y_t
directly to know the true nature
of the couplings of the observed
Higgs boson.



A Direct Probe of Y_t



- m_{top} too large for $H \rightarrow tt$ – must look for production-side dynamics
- Higgs production in association with a top-quark pair (ttH production):



root(s) [TeV]	7	8	13
$\sigma (ttH (125))$ [fb]	90	130	510
$\sigma (tt+\text{jets})$ [fb]	177000	253000	830000
Ratio	5.0E-4	5.1E-4	6.1E-4

- Comparatively small production cross section wrt other Higgs production channels
- Signal dwarfed by tt+jets bkgd
- Spectacular signature – rich final state

Summary of CMS ttH Analyses

H → bb							H → ττ		H → WW,ZZ		H → γγ
							τ _{had}	τ _{had}	τ _{had} + τ _{lep}		
7 TeV	CMS-HIG-12-035 (NN)	JHEP 1305 (2013) 145 (NN)				various					
8 TeV	EPJC 75 (2015) 251 (ME)	CMS-HIG-13-019 (BDT)		CMS-HIG-13-020 (SS-2lep, 3lep, 4 lep)		various					
	JHEP 09(2014)087										
13 TeV	2015	CMS-HIG-16-004		CMS-HIG-15-008							
	2016	CMS-HIG-16-038	CMS-HIG-17-003		CMS-HIG-17-004	CMS-HIG-16-040 – submitted to JHEP					
		CMS-HIG-17-022 – submitted to JHEP (all-had)	CMS-HIG-17-018 – submitted to JHEP								
		CMS-HIG-17-026 – submitted to JHEP (SL,DL)									

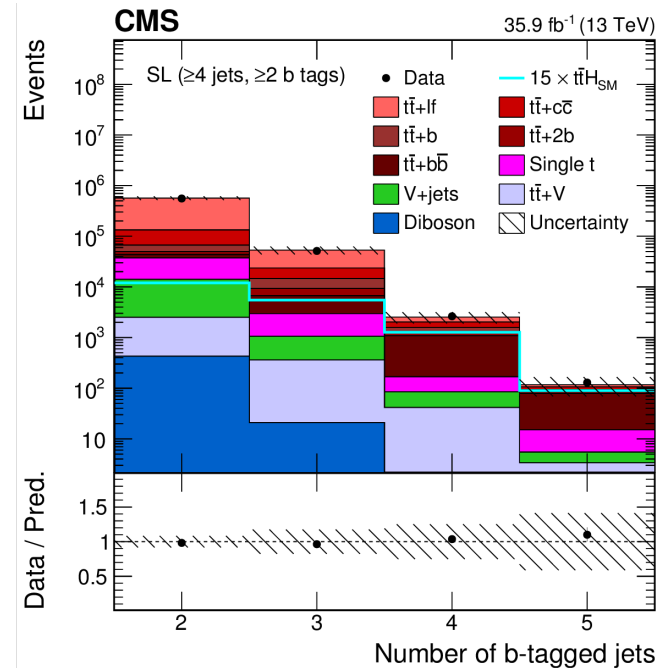
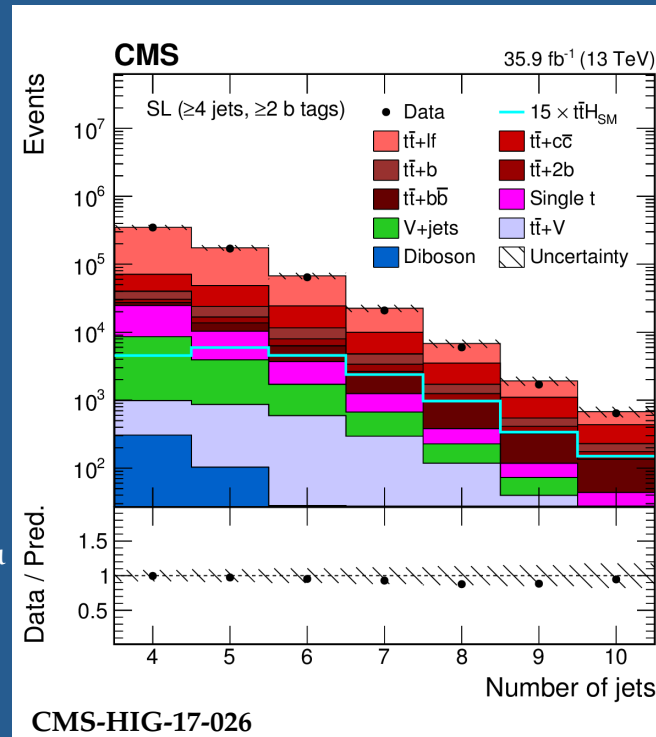
Summary of CMS ttH Analyses

	H→ bb		Multilepton			H → γγ
			τ _{had} τ _{had}	τ _{had} + τ _{lep}		
7 TeV	CMS-HIG-12-035 (NN)	JHEP 1305 (2013) 145 (NN)				various
8 TeV	EPJC 75 (2015) 251 (ME)			CMS-HIG-13-020 (SS-2lep, 3lep, 4 lep)		various
	CMS-HIG-13-019 (BDT)					
			JHEP 09(2014)087			
13 TeV	2015	CMS-HIG-16-004		CMS-HIG-15-008		
	2016	CMS-HIG-16-038	CMS-HIG-17-003		CMS-HIG-17-004	CMS-HIG-16-040 – submitted to JHEP
		CMS-HIG-17-022 – submitted to JHEP (all-had)	CMS-HIG-17-018 – submitted to JHEP			
		CMS-HIG-17-026 – submitted to JHEP (SL,DL)				

$t\bar{t}H, H \rightarrow b\bar{b}$

Overview: $H \rightarrow b\bar{b}$

- $H \rightarrow b\bar{b}$ is a prime target of $t\bar{t}H$ analyses:
 - Largest Higgs BR for $M_H=125$
- CMS considers three topologies:
 - **Single-lepton (SL):**
 - one high p_T iso'd e/μ
 - ≥ 4 jets
 - ≥ 3 b tags
 - **Dilepton (DL):**
 - two opposite-sign e/μ
 - ≥ 4 jets
 - ≥ 3 b tags
 - **Multijet (MJ):**
 - ≥ 7 jets
 - ≥ 3 b tags
- Split selected events into categories based on jet, b-tag multiplicity



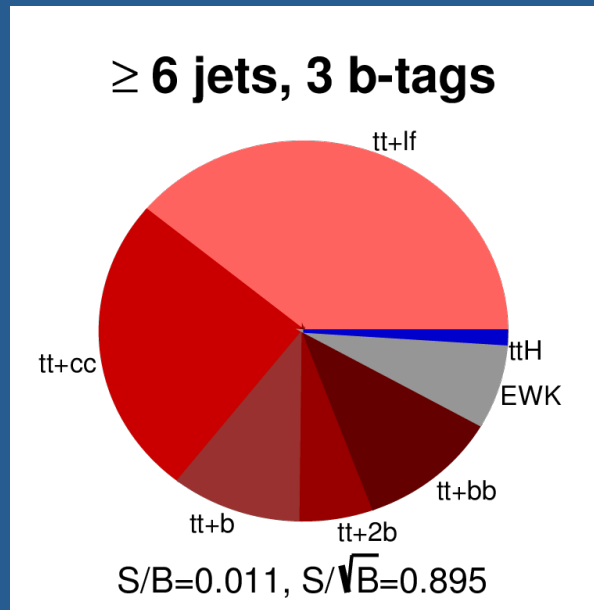
Similar distributions for DL, MJ channels

A discriminant is devised in each category for signal extraction and a simultaneous fit is performed across all categories.

Low-signal categories serve to help constrain backgrounds.

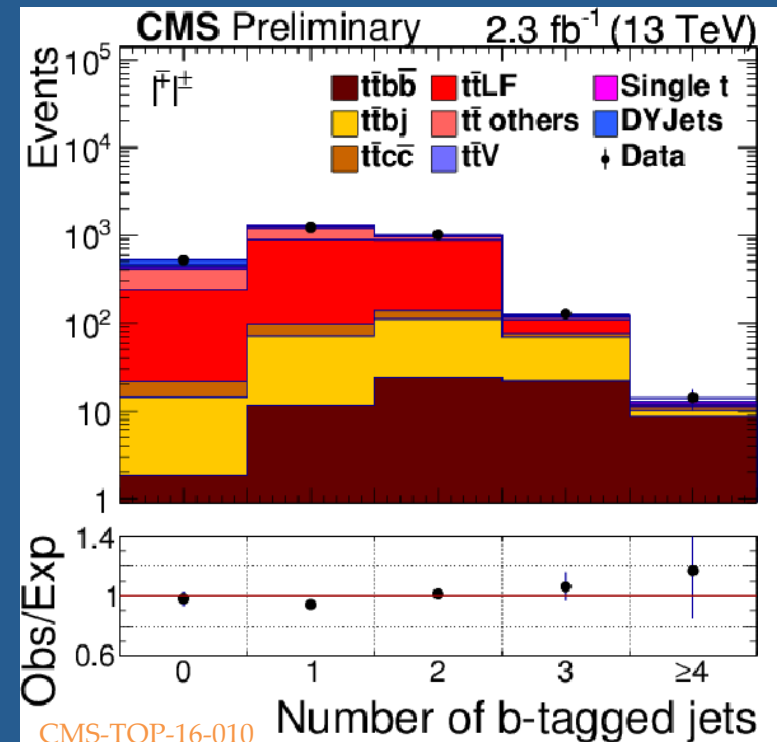
Details of signal extraction in backup.

Big Issue: Understanding the $t\bar{t}$ +HF Background



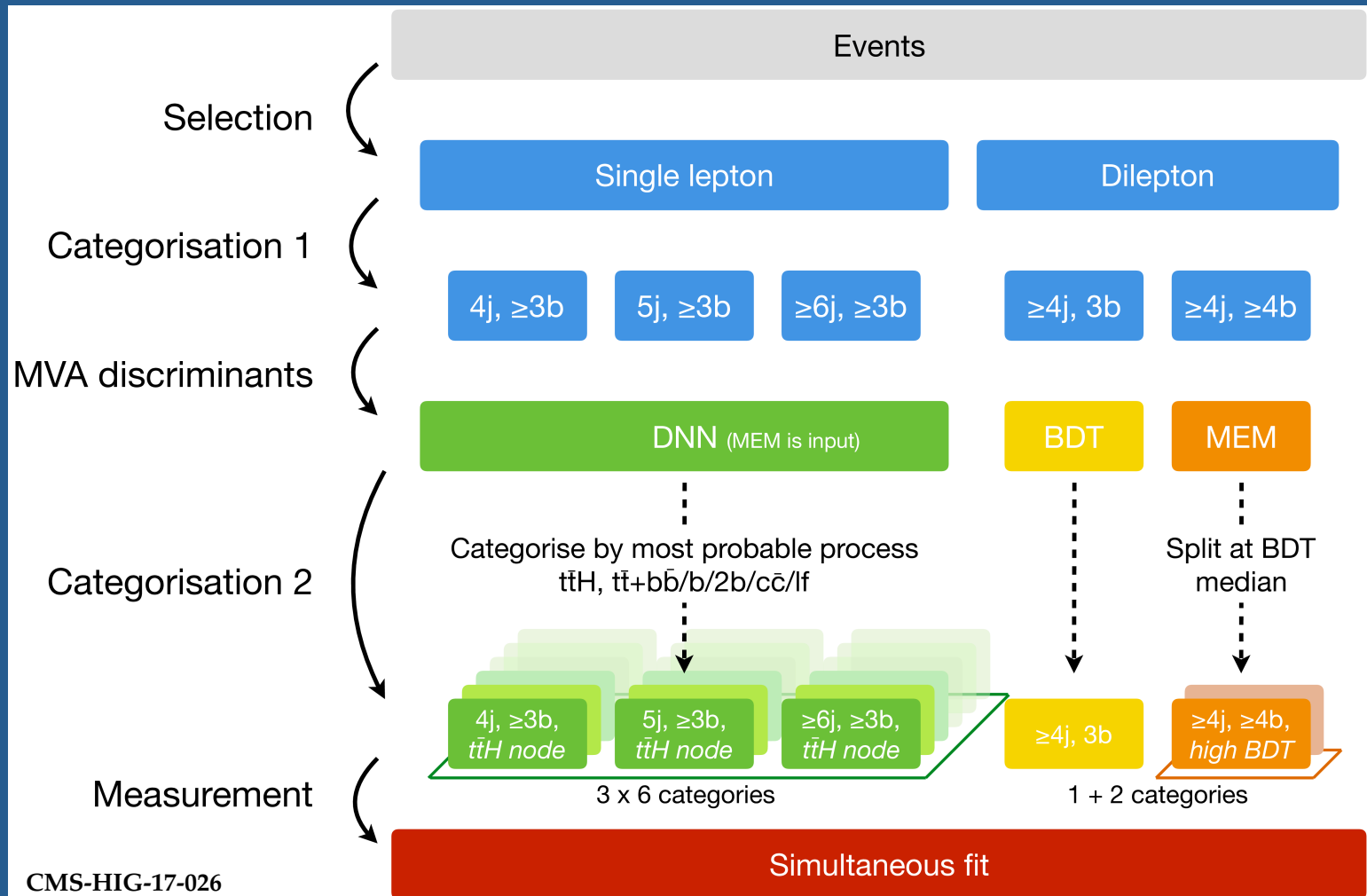
- $t\bar{t}$ +bb production poses irreducible background:
 - Poorly known theoretically
 - Measurements of $t\bar{t}$ bb CRUCIAL

Measurement of $t\bar{t}$ bb production at CMS



- Modeling of $t\bar{t}$ +jets process:
 - Powheg+Pythia8, normalized to NNLO prediction
 - Separate templates for $t\bar{t} + b$, $t\bar{t} + bb$, $t\bar{t} + 2b$, $t\bar{t} + cc$, $t\bar{t} + LF$
 - 50% rate uncertainty per $t\bar{t} + HF$ process, uncorrelated in final fit
 - Among the leading uncertainties
 - Add. sources include parton shower, hadronisation, PDF, ISR/FSR

Signal Extraction: $H \rightarrow b\bar{b}$



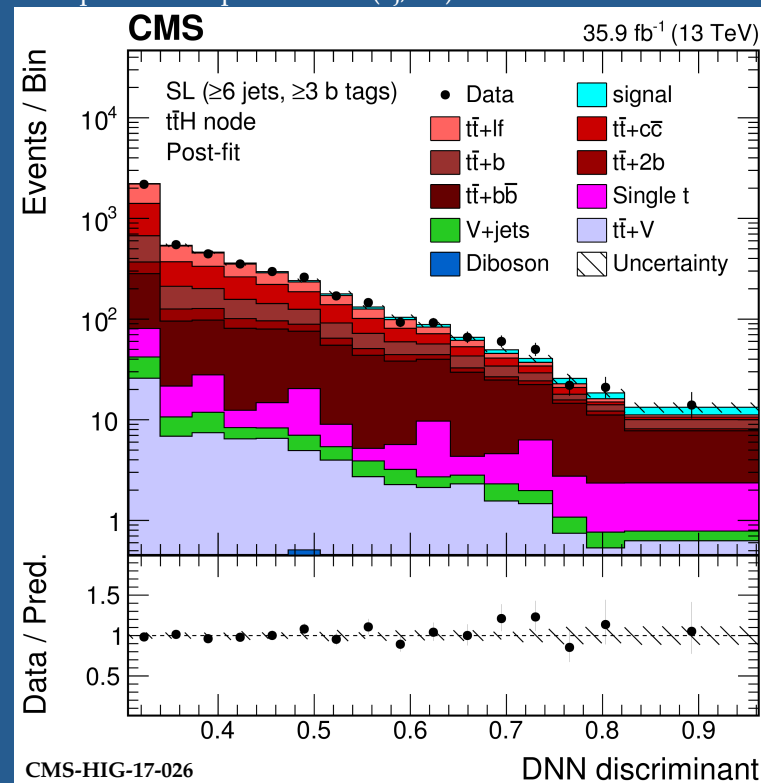
- Challenging signal extraction due to overwhelming irreducible backgrounds – require novel techniques
- Different multivariate techniques were considered for the signal extraction – choice based on best expected sensitivity

Example: Deep Neural Networks

- Neural networks (NNs) have been used in HEP analyses for decades
- Historically, these have been “shallow” networks
 - One input layer with nodes for each of the input variables characterizing the processes
 - One hidden layer with some optimized number of nodes
 - One output layer with, typically, one output node (target output = 1.0 for signal, 0.0 for bkgd)
- Shallow was the way to go:
 - Computationally expensive to train multi-layered networks
 - Very little evident gain
- Things have evolved:
 - Learning algorithms improve
 - Sequencing of NNs afford access to features
 - Cases where “deep” NNs are effective over their simpler counterparts

1. Separate selected events into three categories: $(4j, \geq 3t)$, $(5j, \geq 3t)$, $(6j, \geq 3t)$
2. Design multi-class DNN in each category with 6 output nodes, one for each major bkgd process and one for signal
3. Training proceeds with goal of predicting type of process for each event

Example: $t\bar{t}H$ output node in $(6j, \geq 3t)$:



Example: Deep Neural Networks

- Large parameter space (50+ variables) was considered for the choice of input variables in each category, in both the SL and DL analyses
- Significant campaign to really make an optimized choice

Variable	Definition	SL (4 jets ≥ 3 b tags)	SL (5 jets ≥ 3 b tags)	SL (≥ 6 jets, ≥ 3 b tags)	DL (≥ 4 jets, 3 b tags)	DL (≥ 4 jets, ≥ 4 b tags)
$p_T(\text{jet } 1)$	p_T of the highest- p_T jet	+	+	-	-	-
$\eta(\text{jet } 1)$	η of the highest- p_T jet	-	+	+	-	-
$d(\text{jet } 1)$	b tagging discriminant of the highest- p_T jet	+	+	+	-	-
$p_T(\text{jet } 2)$	p_T of the second highest- p_T jet	-	+	-	-	-
$\eta(\text{jet } 2)$	η of the second highest- p_T jet	+	+	+	-	-
$d(\text{jet } 2)$	b tagging discriminant of the second highest- p_T jet	+	+	+	-	-
$p_T(\text{jet } 3)$	p_T of the third highest- p_T jet	-	+	-	-	-
$\eta(\text{jet } 3)$	η of the third highest- p_T jet	+	+	+	-	-
$d(\text{jet } 3)$	b tagging discriminant of the third highest- p_T jet	+	+	+	-	-
$p_T(\text{jet } 4)$	p_T of the fourth highest- p_T jet	+	+	-	-	-
$\eta(\text{jet } 4)$	η of the fourth highest- p_T jet	+	+	+	-	-
$d(\text{jet } 4)$	b tagging discriminant of the fourth highest- p_T jet	+	-	+	-	-
$p_T(\text{lep } 1)$	p_T of the highest- p_T lepton	-	+	+	-	-
$\eta(\text{lep } 1)$	η of the highest- p_T lepton	+	-	+	-	-
d_b^{avg}	average b tagging discriminant value of all jets	+	+	+	-	-
d_b^{avg}	average b tagging discriminant value of b-tagged jets	+	+	+	+	+
$d_{\text{non-b}}^{\text{avg}}$	average b tagging discriminant value of non-b-tagged jets	-	-	-	+	+
$\Sigma_b (d - d_b^{\text{avg}})$	squared difference between the b tagging discriminant value of a b-tagged jet and the average b tagging discriminant values of all b-tagged jets, summed over all b-tagged jets	+	+	+	-	-
d_b^{max}	maximal b tagging discriminant value of all jets	+	+	+	-	-
d_b^{max}	maximal b tagging discriminant value of b-tagged jets	+	+	+	-	-
d_b^{min}	minimal b tagging discriminant value of all jets	+	+	+	-	-
d_b^{min}	minimal b tagging discriminant value of b-tagged jets	+	+	+	-	-
d_2	second highest b tagging discriminant value of all jets	+	+	+	-	-

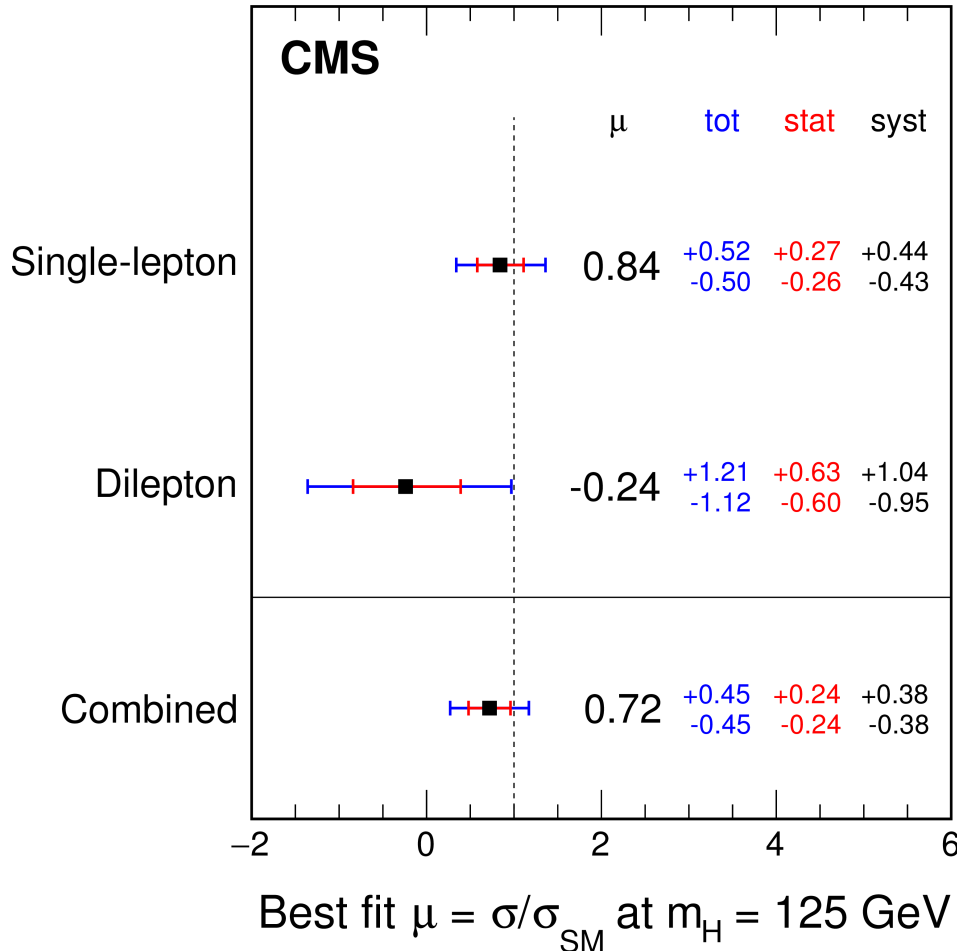
- DNNs were optimal for SL, BDT+MEM in DL categories
- Final fit took these output discriminants in a simultaneous max likelihood fit

Channel	Method	Best-fit μ $\pm \text{tot} (\pm \text{stat} \pm \text{syst})$
Single-lepton	BDT+MEM	$1.0^{+0.69}_{-0.66} \left(\begin{smallmatrix} +0.31 & +0.62 \\ -0.30 & -0.59 \end{smallmatrix} \right)$
Single-lepton	DNN	$1.0^{+0.58}_{-0.55} \left(\begin{smallmatrix} +0.30 & +0.50 \\ -0.29 & -0.47 \end{smallmatrix} \right)$
Dilepton	BDT+MEM	$1.0^{+1.22}_{-1.12} \left(\begin{smallmatrix} +0.65 & +1.04 \\ -0.62 & -0.93 \end{smallmatrix} \right)$
Dilepton	DNN	$1.0^{+1.38}_{-1.36} \left(\begin{smallmatrix} +0.71 & +1.18 \\ -0.69 & -1.18 \end{smallmatrix} \right)$
Combined	BDT+MEM	$1.0^{+0.60}_{-0.57} \left(\begin{smallmatrix} +0.28 & +0.53 \\ -0.27 & -0.51 \end{smallmatrix} \right)$
Combined	DNN	$1.0^{+0.55}_{-0.51} \left(\begin{smallmatrix} +0.27 & +0.47 \\ -0.27 & -0.44 \end{smallmatrix} \right)$

$t\bar{t}H, H \rightarrow b\bar{b}$: Results from SL, DL

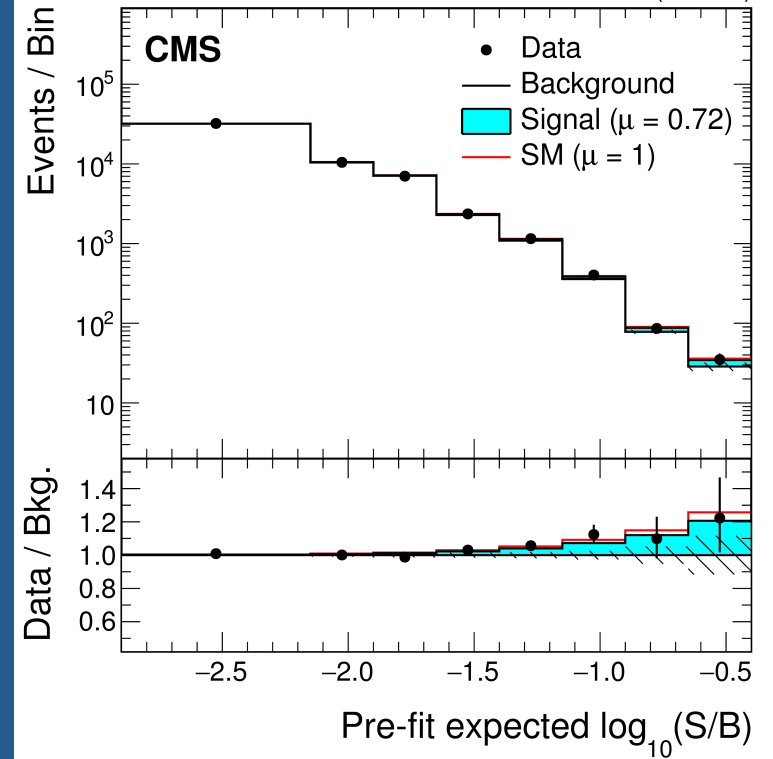
CMS-HIG-17-026

35.9 fb⁻¹ (13 TeV)



CMS-HIG-17-026

35.9 fb⁻¹ (13 TeV)

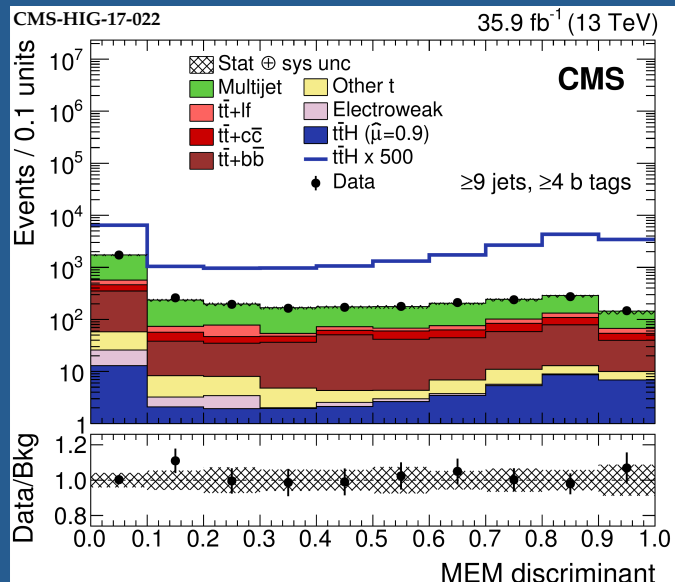


- Best fit: $\mu = -0.72 \pm 0.24$ (stat) ± 0.38 (syst)
- Corresponds to an observed (expected) signal significance of 1.6 (2.2) standard deviations above the background-only hypothesis

$t\bar{t}H, H \rightarrow b\bar{b}$: Results from MJ

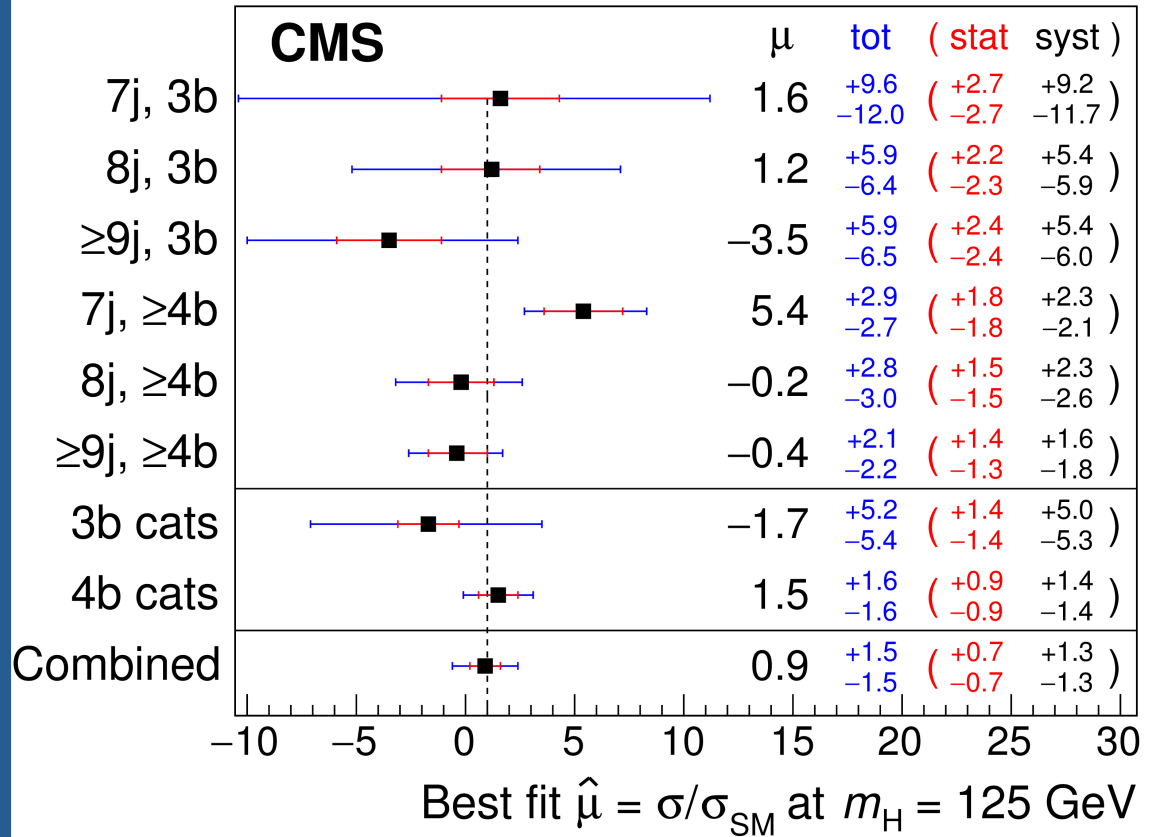
- MJ channel:

- Low sensitivity but high statistics
- Overwhelming QCD background
- Dedicated Matrix Element Method discriminant in each category:



CMS-HIG-17-022

35.9 fb⁻¹ (13 TeV)



- Important to turn over every stone in the river

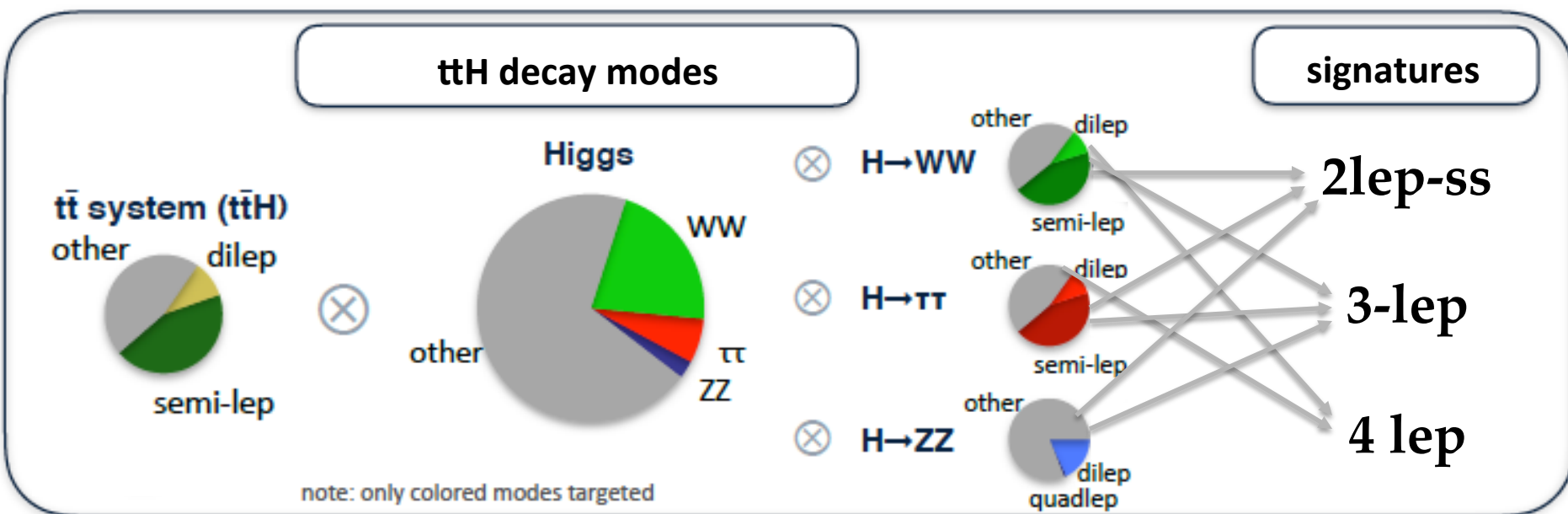
- Value in having another orthogonal sample from which to approach the problem – further insight on systematic uncertainties

$t\bar{t}H, H \rightarrow \text{multileptons (WW, ZZ, } \tau\tau)$

$t\bar{t}H, H \rightarrow \text{multileptons}$

- $t\bar{t}H, H \rightarrow \text{leptons}$:
 - Targeted Higgs decays and BR $H \rightarrow WW^* (\sim 20\%) , \tau\tau (6\%) , ZZ (3\%)$
 - Leptons originate from Higgs and top system
- Targeted experimental signatures include multiple leptons
 - 2 same-sign leptons (2lss)
 - 3 leptons
 - 4 leptons

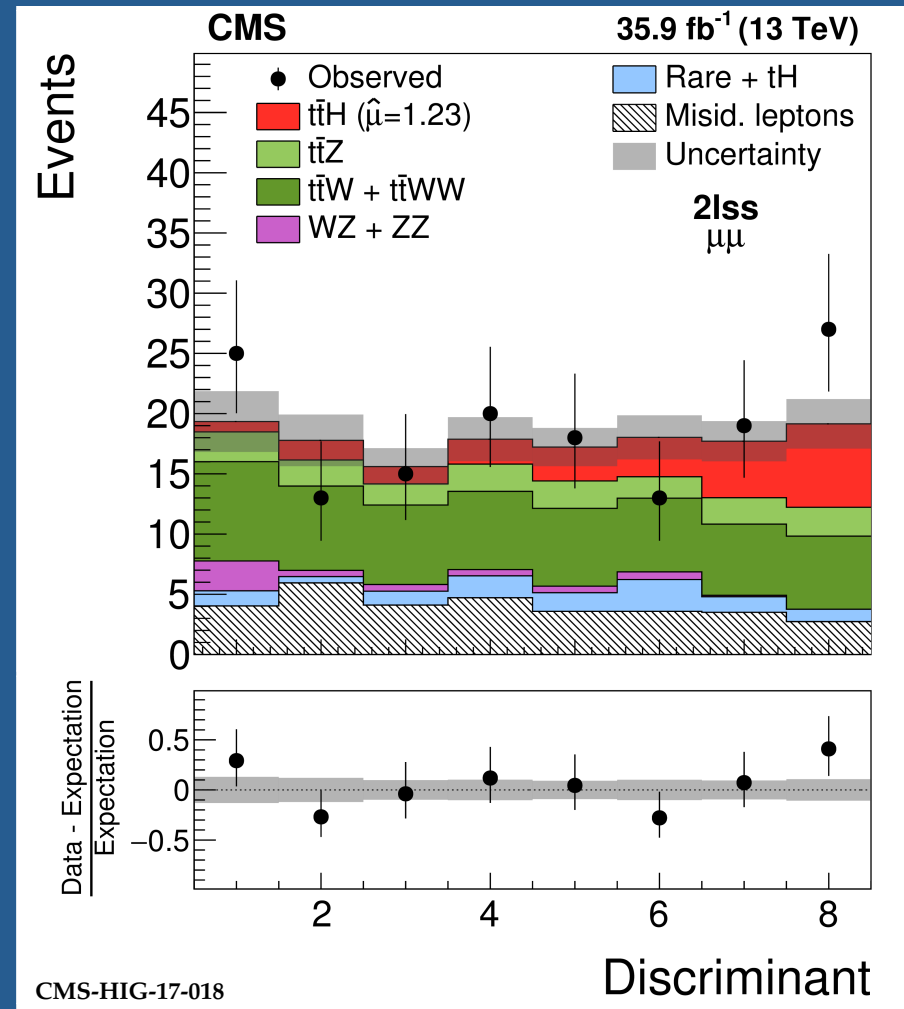
Event selection and signal extraction details in the backup



Low-rate but relatively low-background signatures.

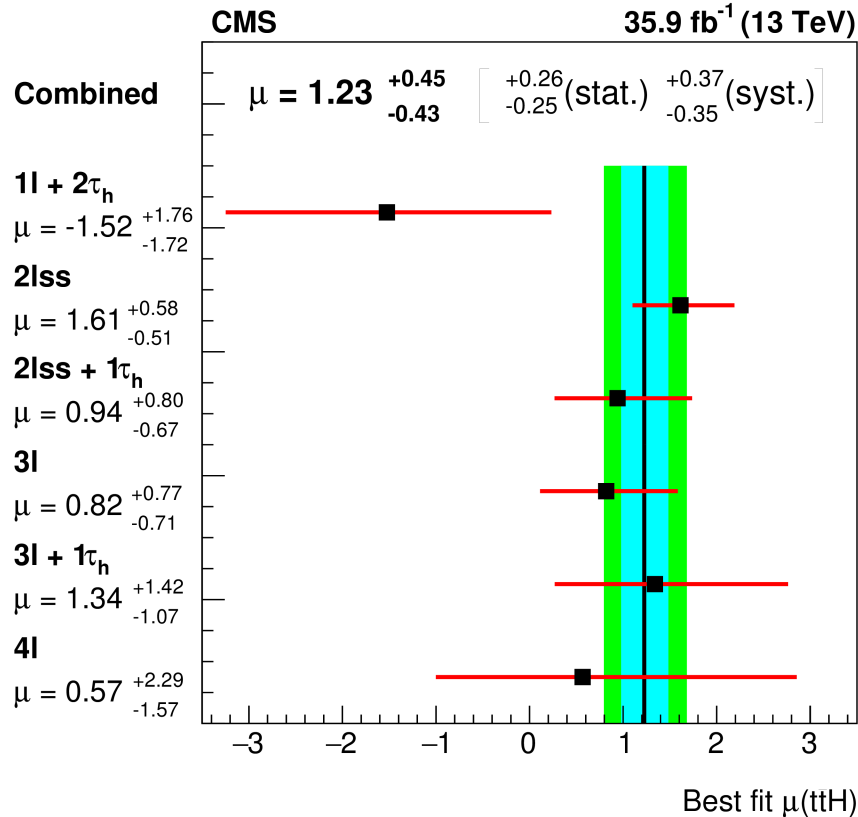
$t\bar{t}H, H \rightarrow$ multileptons

- Six search categories based on the number of e/μ and hadronic τ 's
 - one lepton and two τ_h ($1l + 2\tau_h$)
 - two leptons with same charge ("same-sign leptons") and zero τ_h ($2lss$)
 - two same-sign leptons and one τ_h ($2lss + 1\tau_h$)
 - three leptons and zero τ_h ($3l$)
 - three leptons and one τ_h ($3l + 1\tau_h$)
 - four leptons ($4l$)
- Discrimination from main backgrounds ($t\bar{t}W$, $t\bar{t}Z$, lepton fakes) via a mixture of BDT and matrix element method techniques
- Main systematic uncertainties: lepton efficiencies, lepton mis-id., normalization of irreducible backgrounds

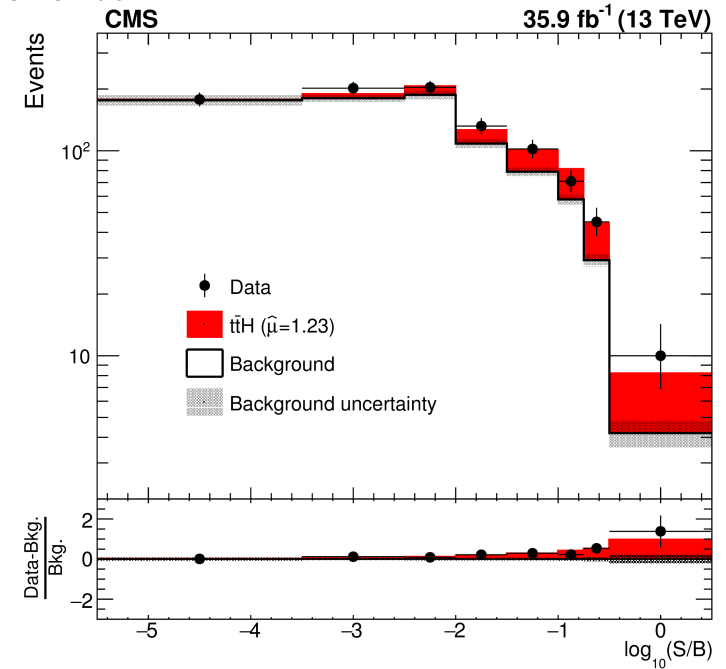


$t\bar{t}H, H \rightarrow$ multileptons: Results

CMS-HIG-17-018



CMS-HIG-17-018



- Best fit: $\mu = 1.23^{+0.26}_{-0.25}(\text{stat})^{+0.37}_{-0.35}(\text{syst})$
- **Significance of observation is 3.2σ** , whereas the expectation, assuming SM-level of $t\bar{t}H$ production was 2.8σ .
- Evidence for $t\bar{t}H$ production from this analysis alone.

$$t\bar{t}H, H \rightarrow \gamma\gamma$$

$t\bar{t}H, H \rightarrow \gamma\gamma$

CMS-HIG-16-040

- Very rare process – yet very pure signature
- Important:
 - Completely reconstructible final state
 - No combinatoric background
 - Hence, only $t\bar{t}H$ search channel in which one can reconstruct a clear mass peak!
- Event selection:
 - 2 photons (requirements on $\text{BDT}_{\gamma\text{ID}}$ and EM deposits), $|\eta| < 2.5$
 - (sub)leading γ $p_T/m_{\gamma\gamma} > 0.5$ (0.25)
 - $100 < m_{\gamma\gamma} < 180$ GeV
 - Categorize events according to $t\bar{t}$ system decay:
 - Leptonic:
 - ≥ 1 $p_T > 20$ e or μ far from γ and $M_Z, \geq 2$ $p_T > 25$ jets, ≥ 1 b-tag
 - Hadronic:
 - special BDT event classifier
 - $=0$ e or $\mu, \geq 3$ $p_T > 25$ jets, ≥ 1 b-tag

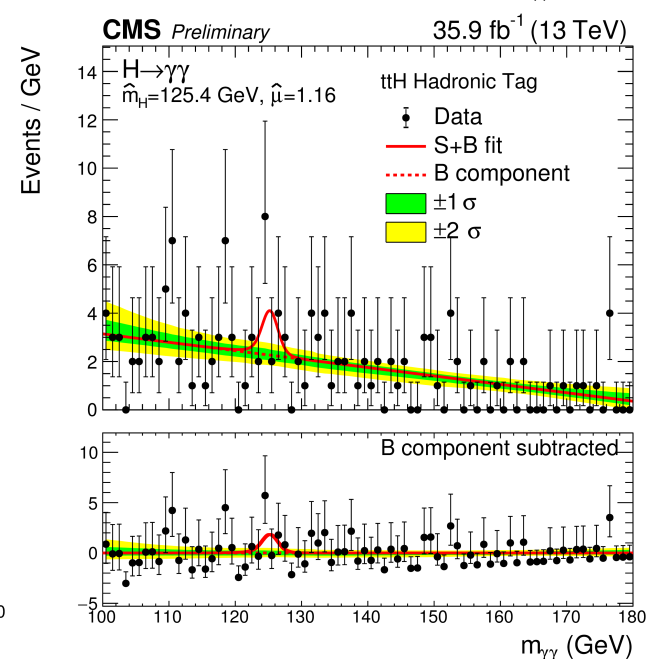
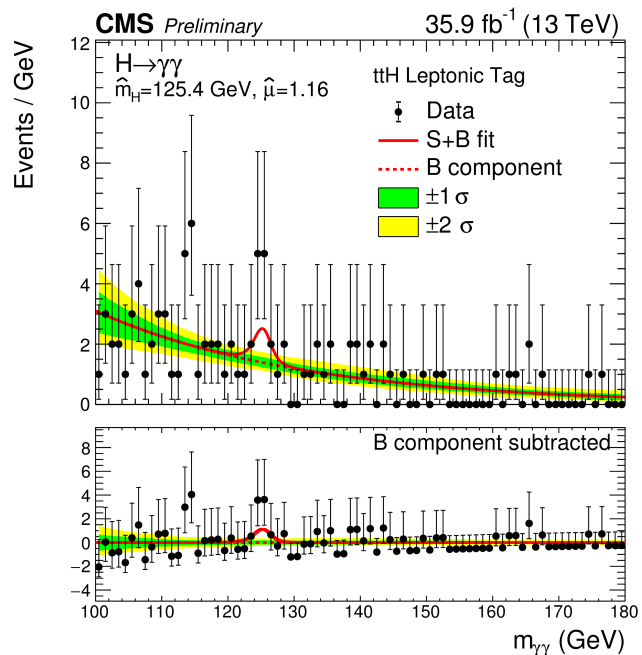
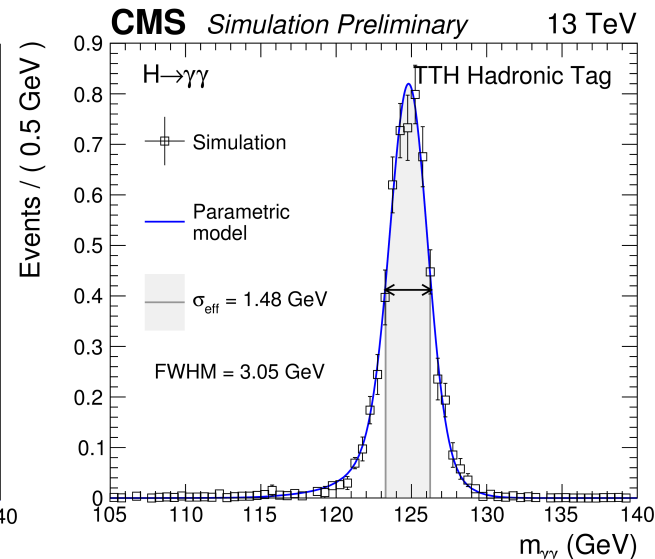
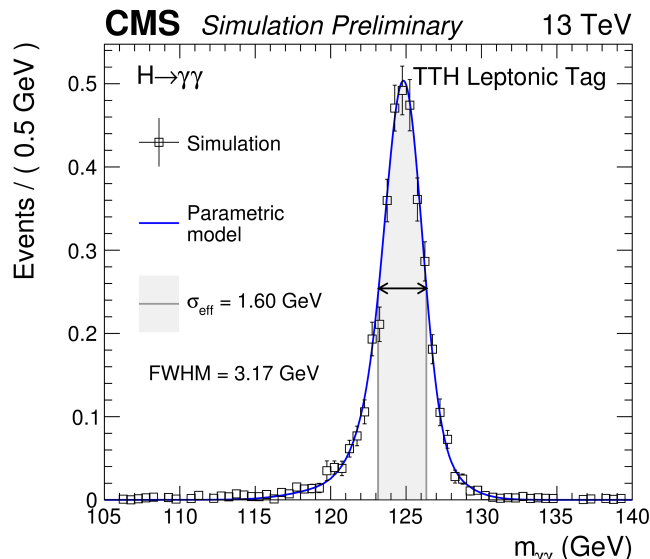
So considering a window of $M_{\gamma\gamma} = 125 \pm 1.5$ GeV, there will be ~ 4.5 background events in the $t\bar{t}H$ Leptonic category.

$S/B \sim 0.85$

Event Categories	SM 125 GeV Higgs boson expected signal											Bkg (GeV ⁻¹)
	Total	ggH	VBF	$t\bar{t}H$	$b\bar{b}H$	tHq	$tH\bar{W}$	WH lep	ZH lep	WH had	ZH had	
$t\bar{t}H$ Hadronic	5.85	10.99 %	0.70 %	77.54 %	2.02 %	4.13 %	2.02 %	0.09 %	0.05 %	0.63 %	1.82 %	2.40
$t\bar{t}H$ Leptonic	3.81	1.90 %	0.05 %	87.48 %	0.08 %	4.73 %	3.04 %	1.53 %	1.15 %	0.02 %	0.02 %	1.50

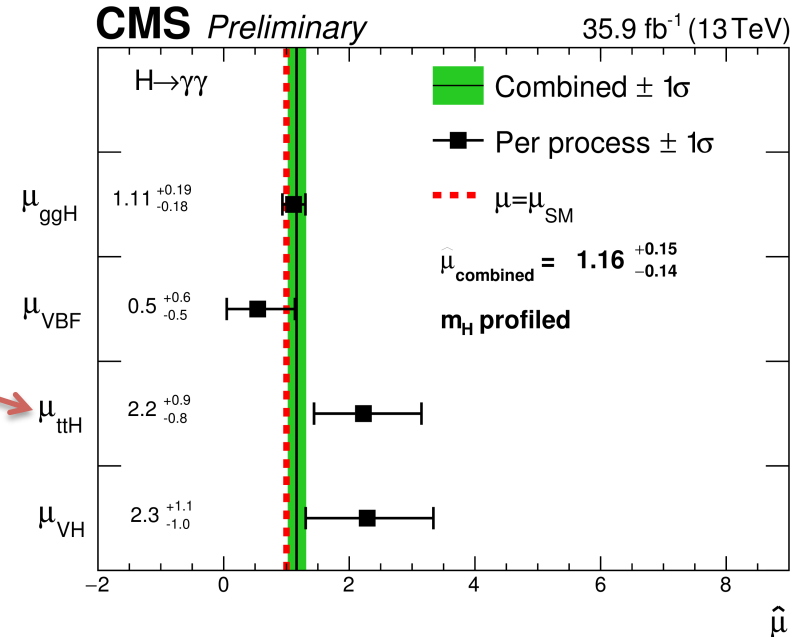
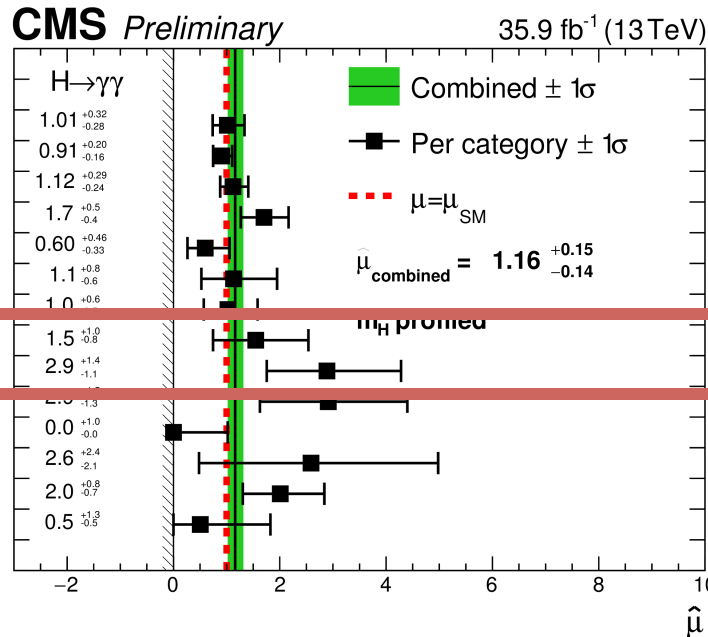
- Backgrounds so low – allows for very simple signal extraction:

- Determine signal shape in $m_{\gamma\gamma}$ exploiting superior resolution of CMS crystal ECAL
- Assume a falling exponential in $m_{\gamma\gamma}$ for the uncorrelated diphoton background
- See what amount of signal is favored in the data for a specific M_H hypothesis



$t\bar{t}H, H \rightarrow \gamma\gamma$

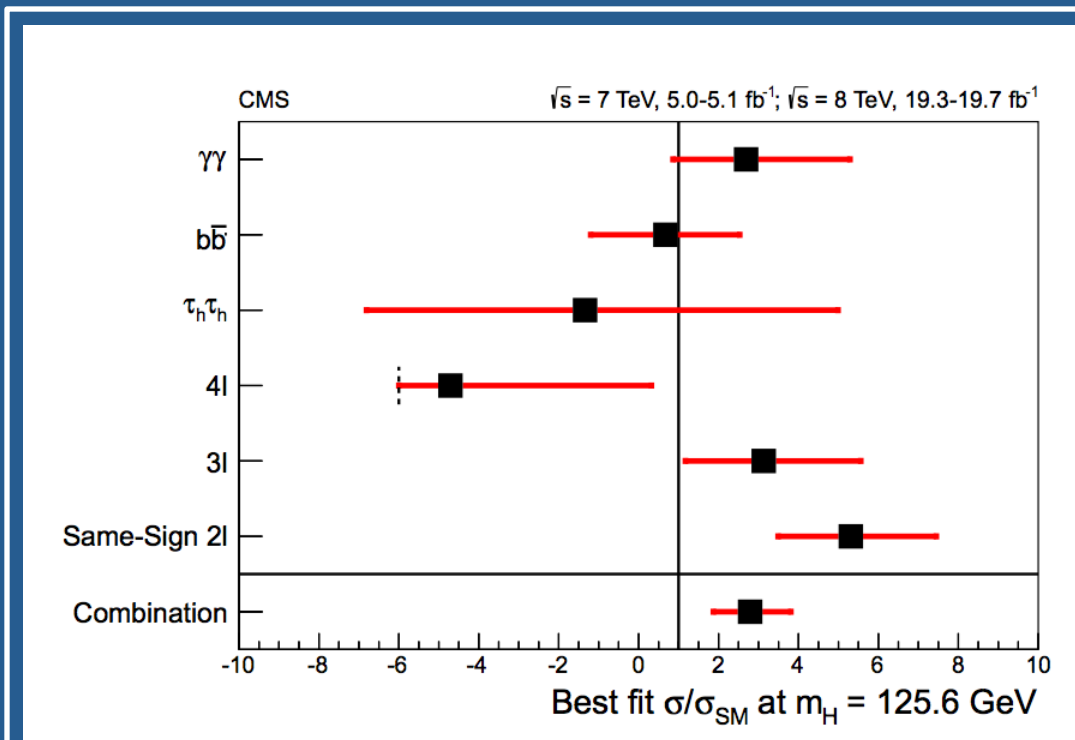
CMS-HIG-16-040



- Results from two $t\bar{t}H$ categories combined:
 - $\mu_{\text{ttH}} = 2.2^{+0.9}_{-0.8}$, assuming $M_H = 125.4$ GeV
 - Uncertainty driven by statistics
- Largely an afterthought...but will be a workhorse
 - Many recent changes in analysis of full 2016 data sample targeted for improving $t\bar{t}H$ sensitivity
 - Good things come to those who wait...and build a solid analysis in the meantime*

Collection of Results

- Analyses highlighted here so far focus on the results from the 2016 LHC run at 13 TeV
- However, as noted earlier, the $t\bar{t}H$ campaign at CMS has been going on for many years, in each channel
- Run 2 $t\bar{t}H$ analyses have exceeded expectations:
 - Benefit from enhanced signal rates going to 13 TeV
 - But, further, analysis techniques have been refined
 - Additional channels were included
- Hence a combination of all published results spanning 7,8,13 TeV eras made sense, given the importance of the signature
- Not a simple exercise:
 - Inclusive signal theory and some background theory uncertainties correlated
 - Experimental uncertainties largely uncorrelated

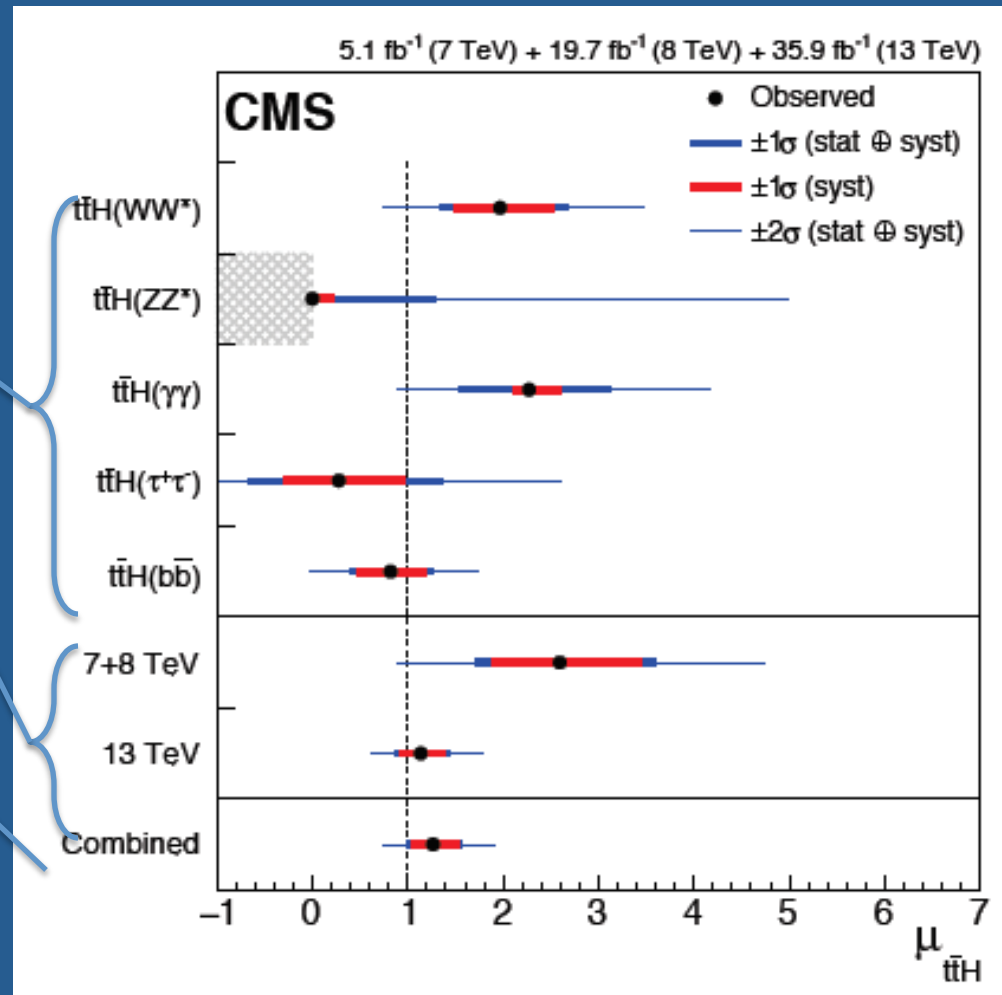


- CMS $t\bar{t}H$ Run 1 legacy:**
 - The best-fit value for the signal strength μ is 2.8 ± 1.0 at 68% confidence level.
 - Excess above the background-only expectation of 3.4 standard deviations.
 - Compared to the SM expectation including the contribution from $t\bar{t}H$, the observed excess is equivalent to a 2-standard-deviation upward fluctuation.

Combined Results

CMS-HIG-17-035, arXiv: 1804.02610

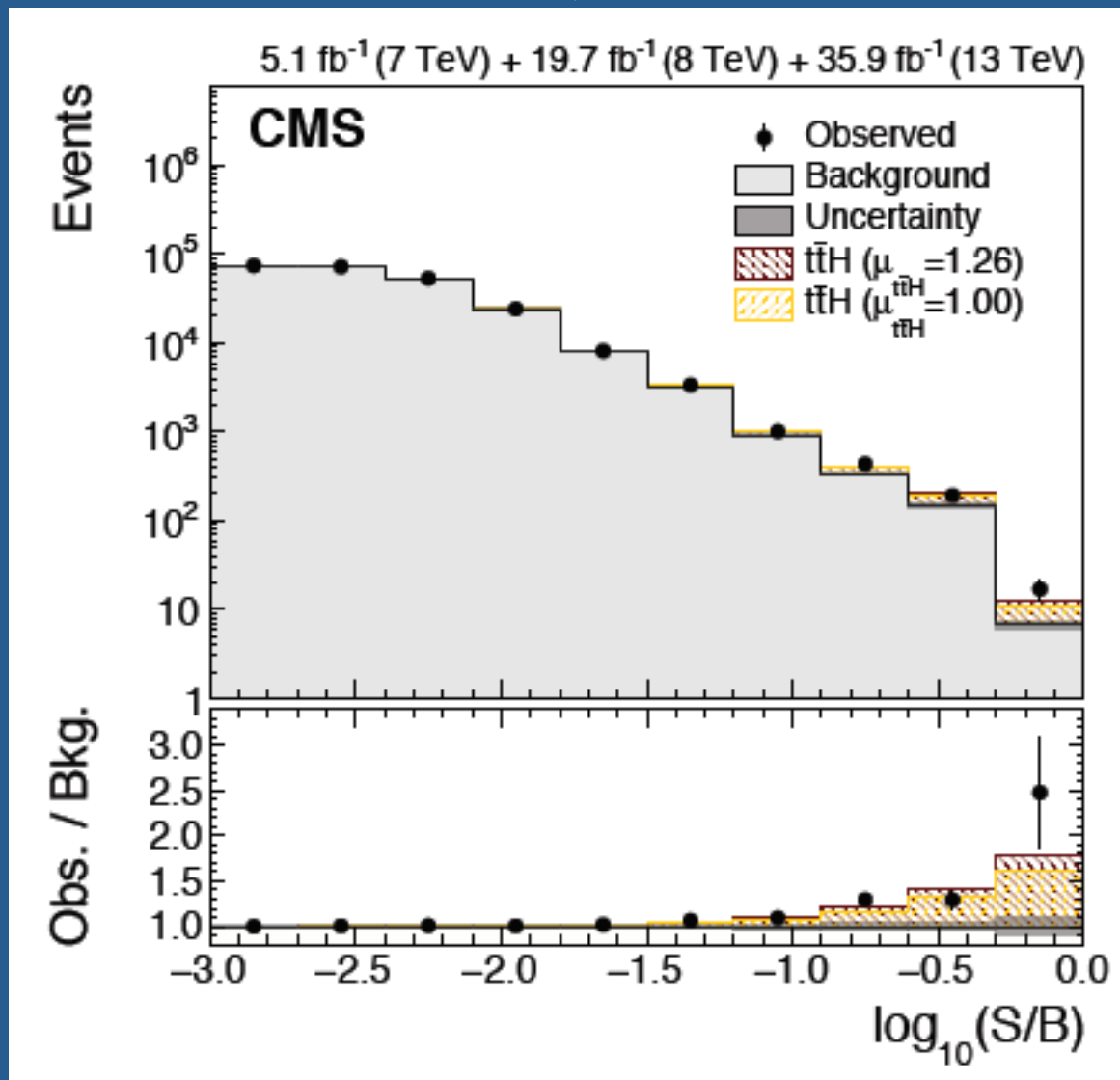
- Measured $t\bar{t}H$ signal strength modifier for three different scenarios:
 - Five independent $\mu_{t\bar{t}H}$, one for each decay mode, fit spanning all eras
 - Two independent $\mu_{t\bar{t}H}$, one for each of Run 1 and Run 2
 - One $\mu_{t\bar{t}H}$ fit incorporating all overall data
- Observations:
 - Results of all fit scenarios consistent with SM prediction $\mu_{t\bar{t}H} = 1.0$
 - Combined fit is driven by 13 TeV analyses
 - $t\bar{t}H, H \rightarrow b\bar{b}$ smallest input uncertainty \rightarrow drives combined result



$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26 \pm 0.16(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{bkg th})^{+0.15}_{-0.07}(\text{sig th})$$

Combined Results

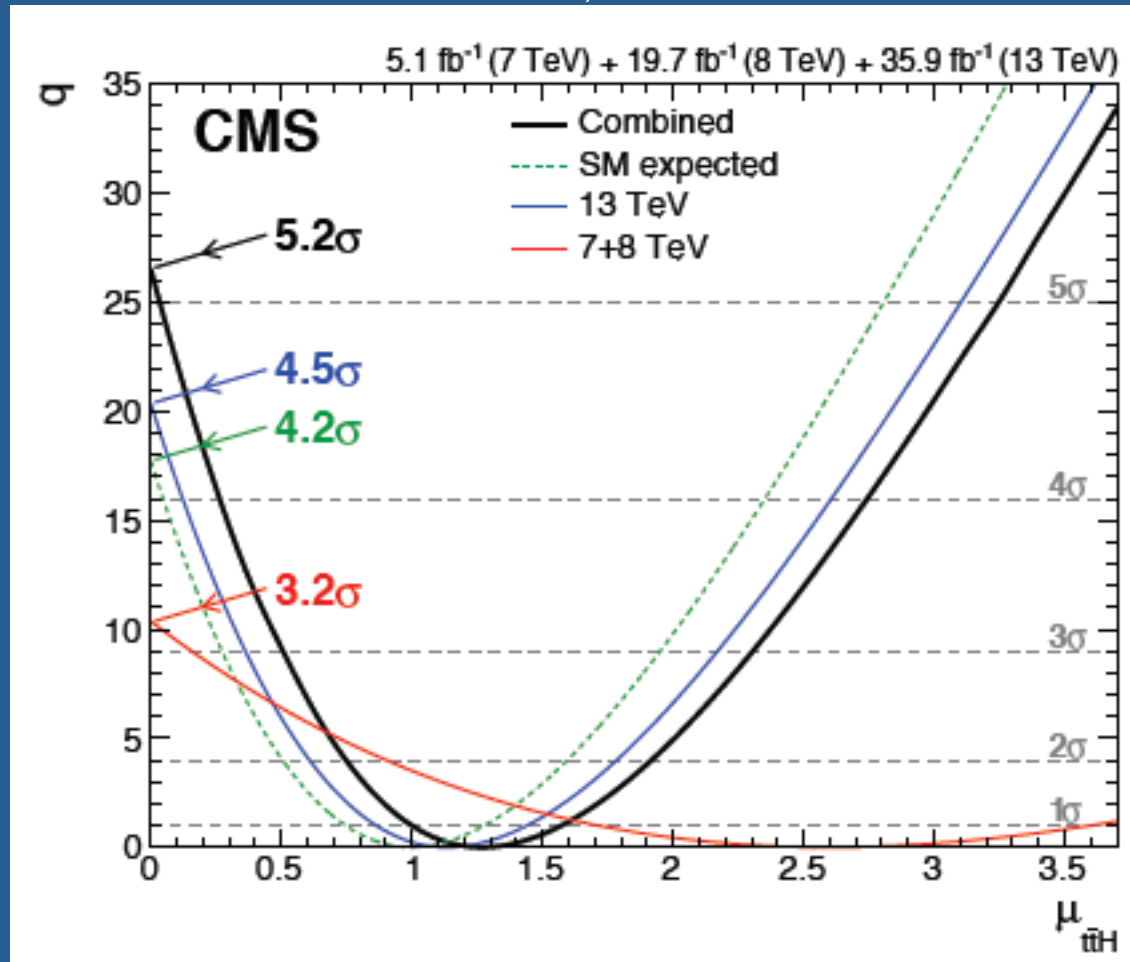
CMS-HIG-17-035, arXiv: 1804.02610



- Really want to see a “money plot”
- Tough business in $t\bar{t}H$:
 - large backgrounds
 - Poor resolution in $H \rightarrow b\bar{b}$
 - Lots of MET in multileptons
 - Many disparate channels
- $H \rightarrow \gamma\gamma$ will provide this someday provided enough stats
- Until then we have plots such as these S/B over the 88 categories in the fit
- Clear excess in most-sensitive bins

First Observation of ttH Production

CMS-HIG-17-035, arXiv: 1804.02610



*Observed significance is 5.2 standard deviations
with respect to the background only ($\mu_{t\bar{t}H} = 0$) hypothesis.*

First observation of the ttH production process.

Summary

- Higgs physics has now moved from the search and discovery phase into a precision measurement era
- A few crucial characteristics of the Higgs boson remain to be measured – the most foremost being the coupling between the top quark and the Higgs
- The ttH campaign at CMS has been proceeding since 2011, incorporating analyses at 7,8,13 TeV conducted in all primary Higgs decay channels
- CMS has performed a combination of all published ttH results and achieved the first observation of the ttH production process
- First direct measurement of the top-Higgs coupling is among the primary goals of the LHC physics program.
- The article CMS-HIG-17-035, arXiv: 1804.02610 has been accepted for publication in PRL -- just received notification this afternoon

US Institutes Played a Major Role



Cornell University®



What's Next

- Near term:
 - Establish $t\bar{t}H$ in all accessible decay channels
 - We have some work to do to make this happen:
 - Improve understanding of $t\bar{t}+H$ process and uncertainties
 - Improve theoretical understanding of $t\bar{t}V$
 - Improve upon already-mature treatment of non-prompt leptons
- Longer term
 - SM-driven backgrounds to $t\bar{t}H$, $H \rightarrow \gamma\gamma$, ie $t\bar{t}\gamma\gamma^*$ at NLO
 - Refine background models
 - Increase purity
 - Differential cross sections

Things like EFTs / top partners / exotic 4th gen / 2HDM / etc look like SM top-Higgs...until you look closely, in the tails.

We will enter that regime in the future – best to lay the groundwork now.

Backup